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ADVANCED SPACE ENGINE
POWERHEAD BREADBOARD ASSEMBLY SYSTEM STUDY

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16. Abstract

The objective of this study was to establish a preliminary design of a Powerhead Breadboard Assembly (PBA) for an 88 964-Newton (20,000-pound) thrust oxygen/hydrogen staged combustion cycle engine for use in orbital transfer vehicle propulsion. Existing turbopump, preburner, and thrust chamber components were integrated with interconnecting ducting, a heat exchanger, and a control system to complete the PBA design. Cycle studies were conducted to define starting transients and steady-state balances for the completed design. Specifications were developed for all valve applications and the conditions required for the control system integration with the facility for system test were defined.

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FOREWORD

The work herein was conducted from December 1976 to June 1977 by personnel from the Advanced and Propulsion Engineering Units at Rocketdyne, a division of Rockwell International, under Contract NAS3-20386. Mr. Dean Scheer, Lewis Research Center, was NASA project manager. At Rocketdyne Mr. H. G. Diem, Program Manager, Mr. A. T. Zachary, Project Manager, and Mr. Richard Campbell, Project Engineer were responsible for the direction of the program.

Important contributions to the conduct of the program and to the preparation of the report material were made by the following Rocketdyne personnel:

Dynamic Modeling	Mr. J. Meadville
Heat Exchanger	Mr. J. Shoji
Controls	Mr. G. Smith
Engine Design	Mr. H. Marker
Controls	Mr. J. Absalom

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SUMMARY

The objective of this study was to establish a preliminary design of a Powerhead Breadboard Assembly (PBA) for an 88 964-Newton (20,000-pound) thrust oxygen/hydrogen staged-combustion cycle engine with engine operating conditions suitable for and applicable to orbital transfer vehicle propulsion. This assembly consists of an existing thrust chamber assembly, preburner, igniters, hydrogen turbopump, and oxygen turbopump previously tested on other contracts. On this program, preliminary design was accomplished on the interconnecting ducting, a heat exchanger, and the control system required to complete the PBA. The program also included cycle studies to determine steady-state balances and start transients.

The first cycle balances conducted on the baseline configuration indicated that there was insufficient temperature on the hydrogen side of the heat exchanger to vaporize the main chamber oxidizer during tank head idle and the tank pressurization oxidizer flow during powered idle. Alternate heat exchanger locations were examined, and the heat exchanger was relocated and changed to a two-fluid device as shown in Fig. 1. In this configuration, the turbopumps are assumed to be mechanically locked to prevent rotation during tank head idle. The main fuel valve is fully open because of the minimum ΔP required to allow enough fuel flow to operate the heat exchanger.

The final idle mode balances are presented in Table 1 and the steady-state balances in Table 2.

Specifications were developed for each PBA valve application. The main LOX, preburner LOX, and main fuel valve are ball valves of similar design with electric actuators and pneumatic override actuators. Prototype valves have already been fabricated and tested by Rocketdyne. The facility inlet valves will use existing J-2 main fuel valves. The GOX shutoff valve and igniter valves are direct acting solenoids selected from existing commercial valve suppliers. The fuel shunt valve is a pressure actuated ΔP limiting check valve of Rocketdyne design. Controllers for the servovalve are presently in use on a preburner/thrust chamber test program and will require only card replacement to be used for mixture ratio and thrust control. The facilities required for timing and sequence control are presently being used for the preburner/thrust chamber testing. An instrumentation list and a redline list are also included in the report.

Analysis of the heat exchanger requirements during tank head idle, powered idle, and mainstage is included with the analysis of the final design heat exchanger resulting in a flat copper plate 21.6 cm (8.5 inches) wide by 61 cm (24 inches) long with oxygen channels on one side, fuel on the other, and manifolds on each end.

A layout was made of the assembled PBA components (Fig. 2) including the newly designed heat exchanger and the additional valves. The preliminary structural analysis of the PBA interconnect lines and heat exchanger was performed to show

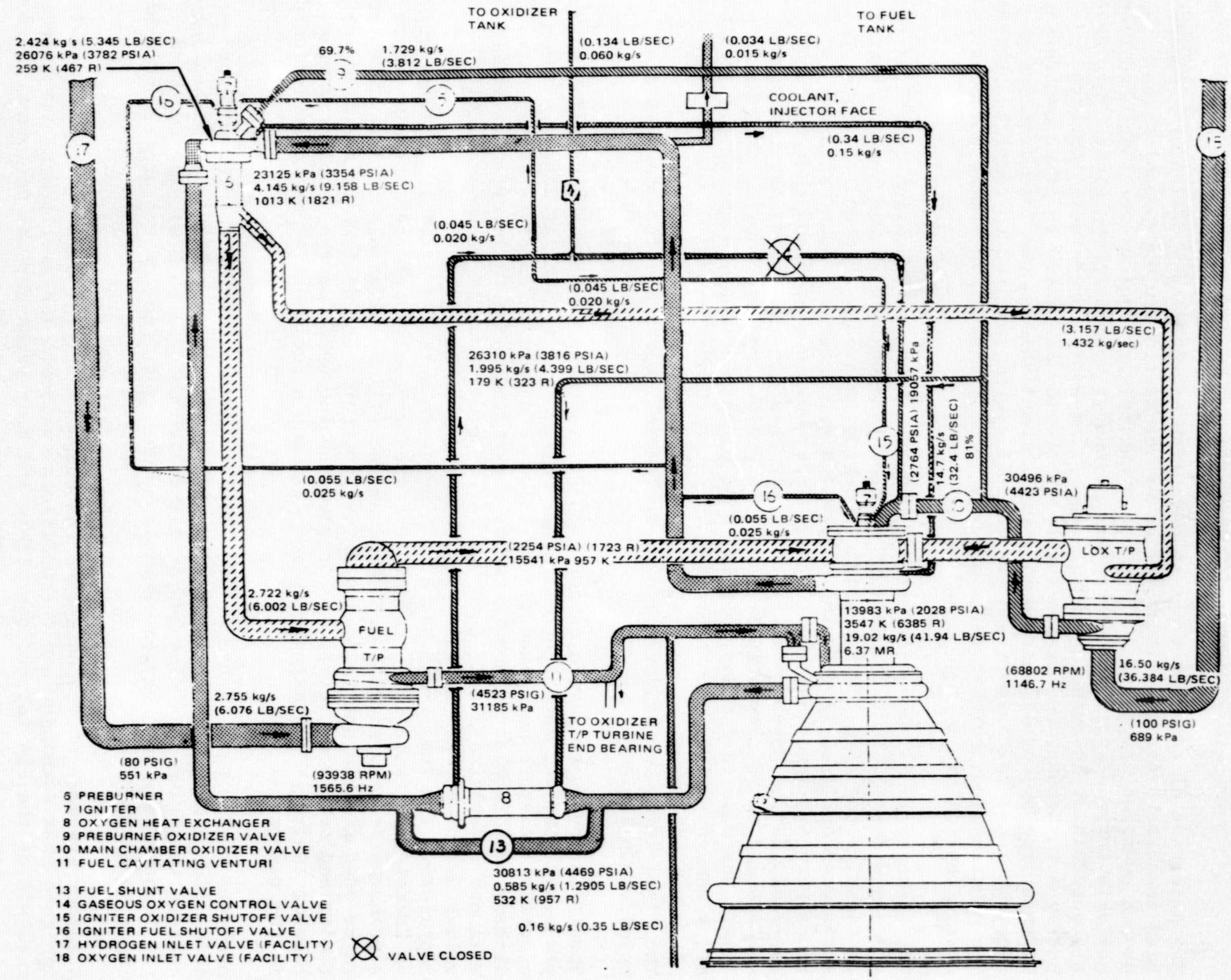

Figure 1. PBA System Schematic (6.0 MR)

TABLE 1. POWERHEAD BREADBOARD IDLE MODE BALANCES

Parameter	Tank Head Idle		Pumped Idle	
Chamber Pressure, kPa (psia)	62	(9.0)	1 289	(187)
Mixture Ratio	2.00		2.03	
Chamber Temperature, K (R)	1 885	(3393)	1 902	(3423)
Fuel Pump Discharge Pressure, kPa (psia)	171.7	(24.9)	3 213	(466)
Fuel Pump Speed, rps (rpm)	---		423	(25,370)
Fuel Pump Flowrate, kg/s (lb/sec)	0.029 26	(0.0645)	0.660	(1.3417)
Fuel Turbine Flowrate, kg/s (lb/sec)	0.018 6	(0.041)	0.421 8	(0.930)
Oxidizer Pump Discharge Pressure, kPa (psia)	172.4	(25.0)	4 371	(634)
Oxidizer Pump Speed, rpm (rpm)	---		411.4	(24,689)
Oxidizer Pump Flowrate, kg/s (lb/sec)	0.058 9	(0.125)	1.232	(2.715)
Oxidizer Turbine Flowrate, kg/s (lb/sec)	0.009 5	(0.021)	0.212	(0.468)
Turbine Inlet Pressure, kPa (psia)	91.0	(13.2)	1 896	(275)
Turbine Inlet Temperature, K (R)	165	(298)	112	(200)

TABLE 2. POWERHEAD BREADBOARD STEADY-STATE BALANCES

	Engine Mixture Ratio					
	5.5		6.0		6.5	
Main Fuel Pump						
Inlet Pressure, kPa (psia)	551	(80)	551	(80)	551	(80)
Flowrate, kg/s (lb/sec)	2.920	(6.439)	2.755	(6.08)	2.66	(5.86)
Discharge Pressure, kPa (psia)	32 695	(4724)	31 185	(4523)	29 744	(4314)
Speed, rps (rpm)	1 621.8	(97,309)	1 567	(93,938)	1 520	(91,195)
Turbine Inlet Pressure, kPa (psia)	23 918	(3469)	23 056	(3344)	22 373	(3245)
Turbine Flowrate, kg/s (lb/sec)	2.892	(6.376)	2.722	(6.00)	2.582	(5.69)
Turbine Discharge Pressure, kPa (psia)	15 270	(2280)	15 541	(2254)	15 395	(2231)
Main Oxidizer Pump						
Inlet Pressure, kPa (psia)	689	(100)	689	(100)	689	(100)
Flowrate, kg/s (lb/sec)	16.04	(35.364)	16.5	(36.384)	16.95	(37.37)
Discharge Pressure, kPa (psia)	35 232	(5710)	30 496	(4423)	26 683	(3820)
Speed, rps (rpm)	1 212.7	(72,767)	1 147	(68,802)	1 084	(65,613)
Turbine Inlet Pressure, kPa (psia)	23 918	(3469)	23 056	(3344)	22 373	(3245)
Turbine Flowrate, kg/s (lb/sec)	1.516	(3.351)	1.427	(3.146)	1.353	(2.984)
Turbine Discharge Pressure, kPa (psia)	15 270	(2280)	15 541	(2254)	15 395	(2231)
Preburner						
Preburner Chamber Pressure, kPa (psia)	23 993	(3480)	23 125	(3354)	22 429	(3253)
Preburner Temperature, K (R)	1 007	(1813)	1 013	(1821)	1 020	(1836)
Preburner Total Flowrate, kg/s (lb/sec)	4.40	(9.70)	4.145	(9.16)	3.939	(8.606)
Chamber Pressure, kPa (psia)	13 982	(2028)	13 932	(2028)	13 982	(2028)
Mixture Ratio	5.83		6.37		6.91	
Flowrate, kg/s (lb/sec)	18.72	(41.28)	19.02	(41.94)	19.34	(42.63)
Dump Nozzle Flowrate, kg/s (lb/sec)	0.16	(0.36)	0.16	(0.35)	0.15	(0.34)

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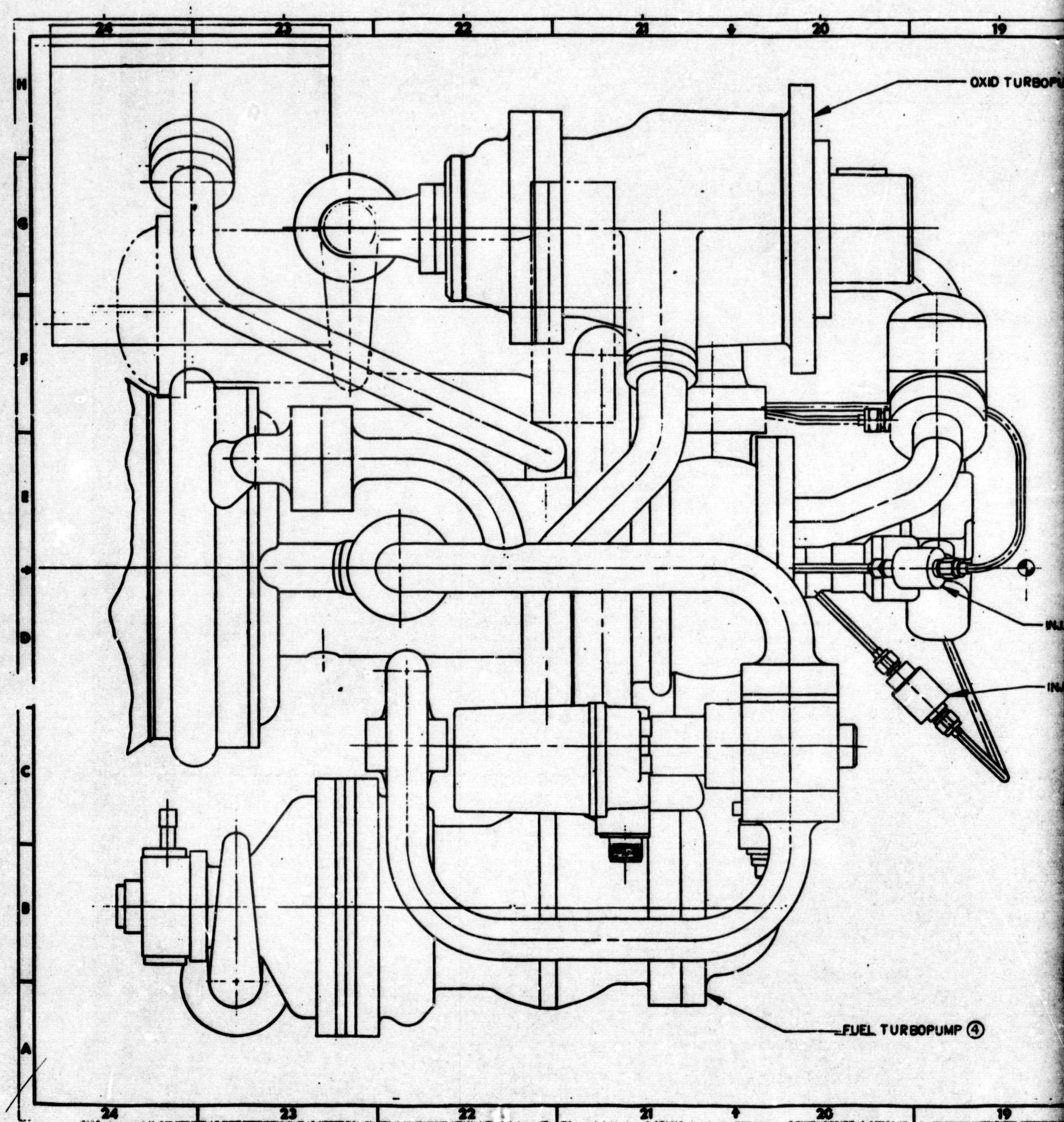
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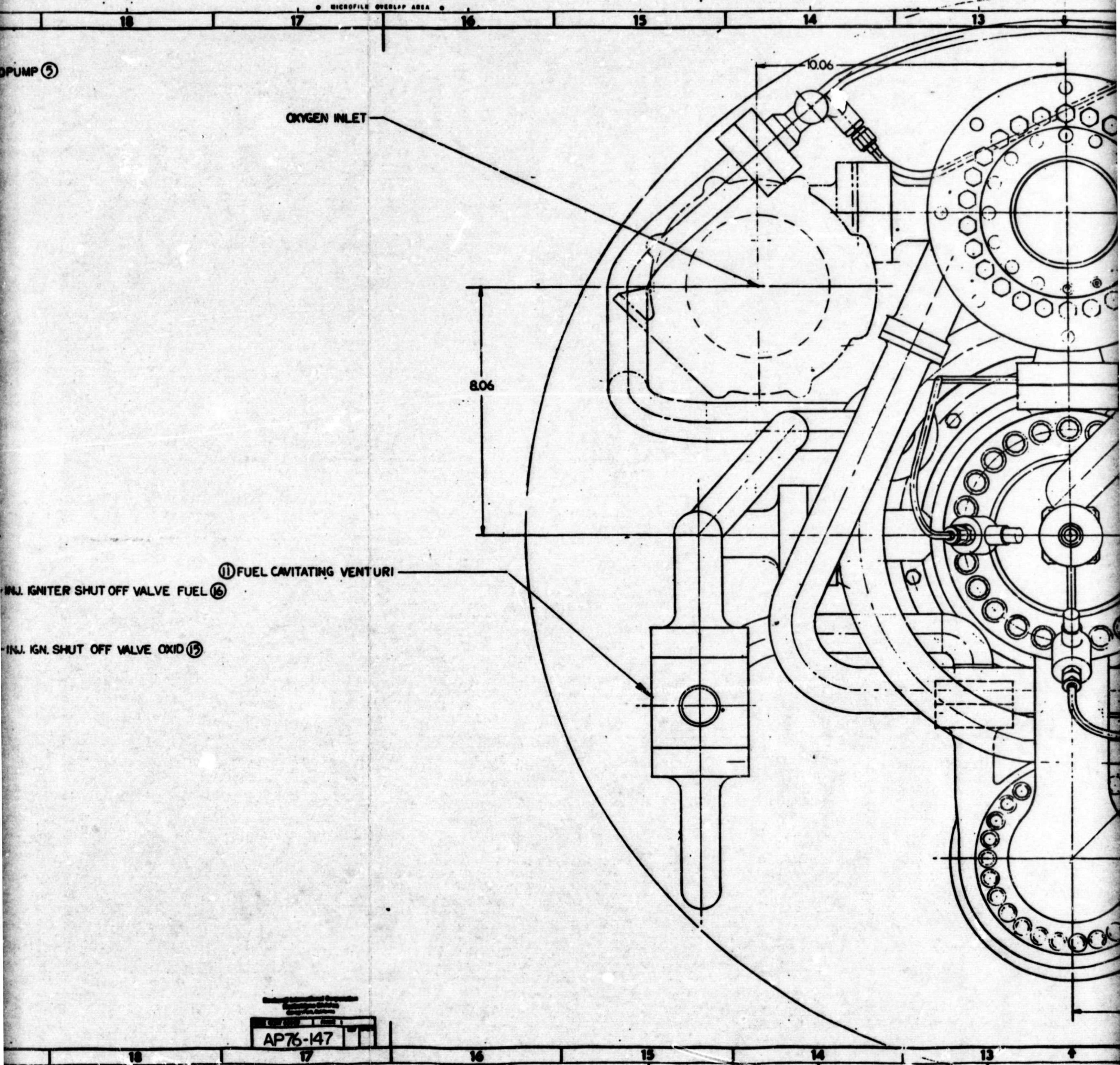

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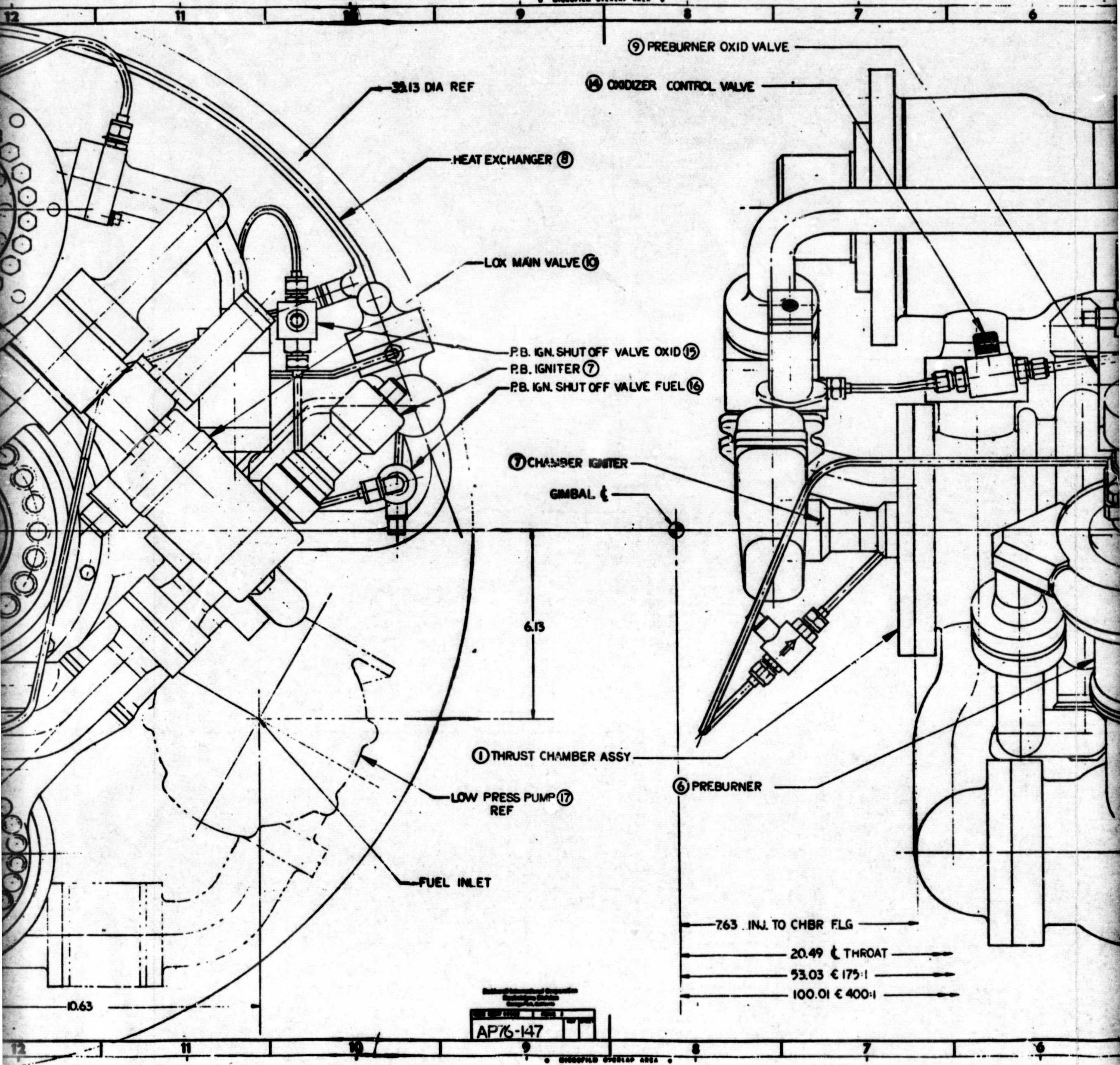

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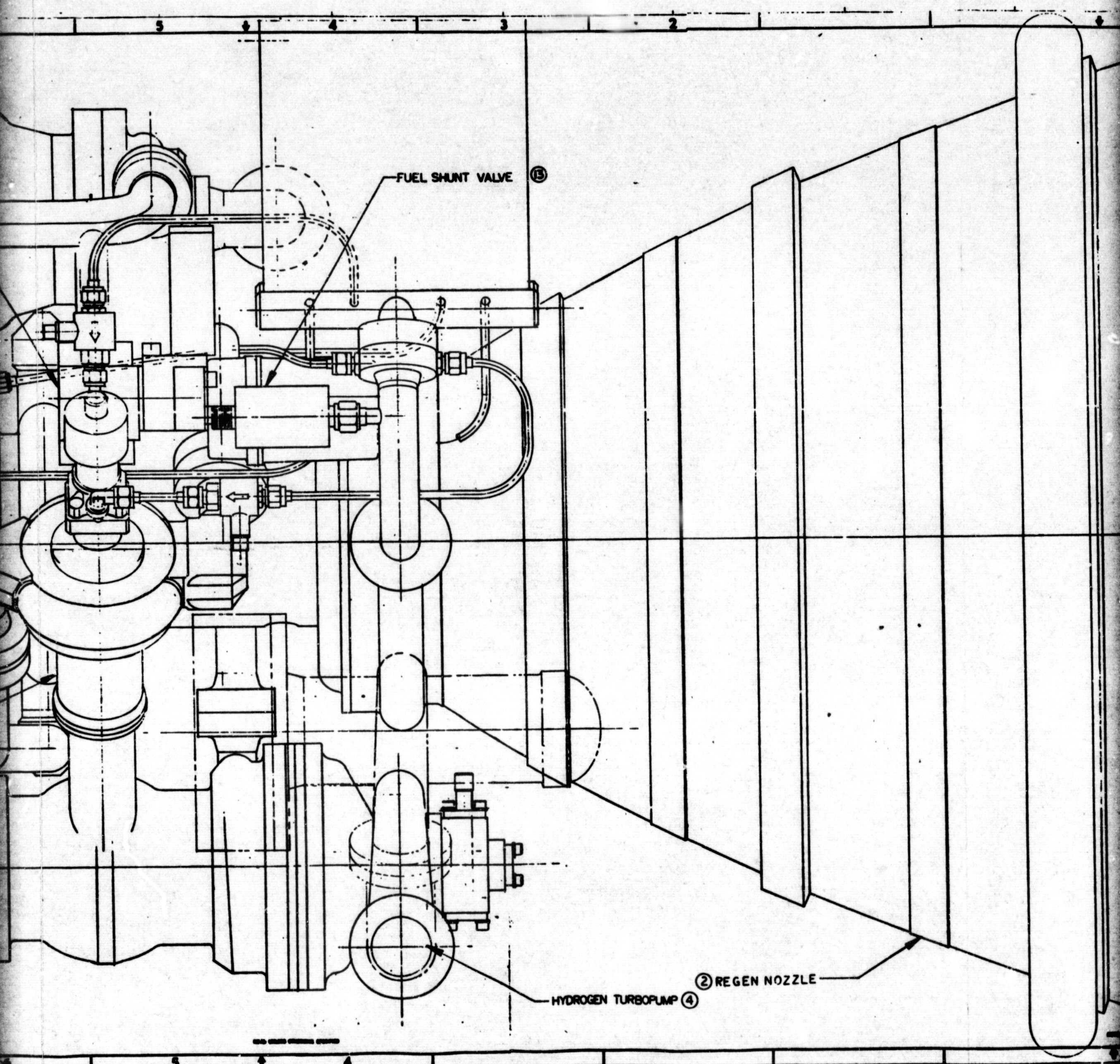

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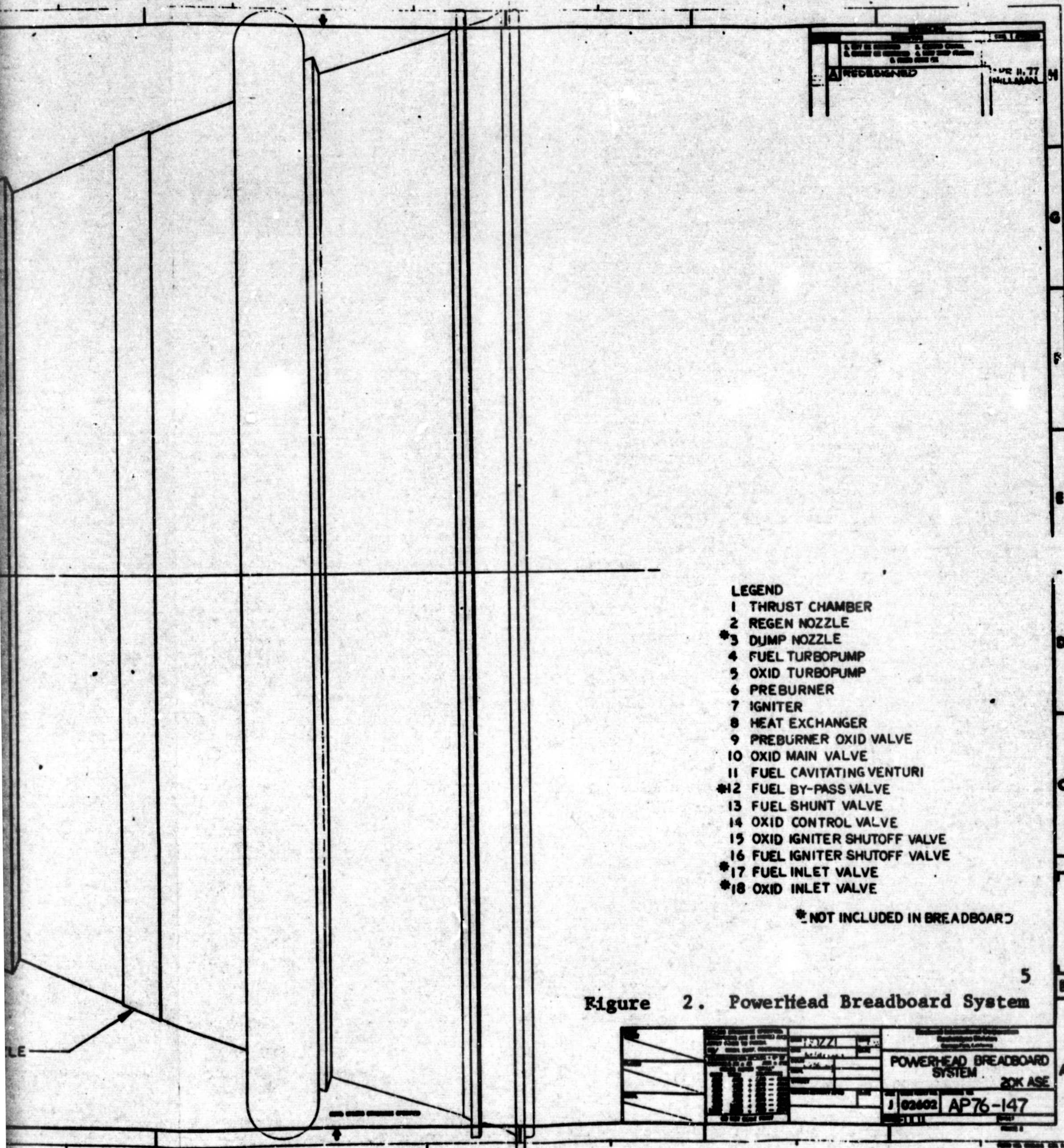


Figure 2. PowerHead Breadboard System

workability of the prepared configuration and design. Results indicate that the proposed routings and heat exchanger design are structurally feasible. Design layouts are also included of the heat exchanger and Rocketdyne ball valves.

As an alternative to mechanically locking the turbopumps during tank head idle mode, a configuration using a bypass line from the preburner outlet to the main injector inlet was examined. Allowing the turbopumps to turn during tank head idle mode and limiting maximum speed during chilldown by bypassing fuel around the turbine permits use of the cavitating venturi main fuel valve while still providing normal heat exchanger operation. Consideration should be given to evaluating this alternative configuration on a PBA test program.

INTRODUCTION

A comprehensive program has been in progress at NASA-LeRC since 1972 to develop the component technology required for an advanced, high-pressure, staged-combustion cycle hydrogen/oxygen engine in the 88 964-Newton (20,000-pound) thrust class. Following Air Force funded studies in 1971, which showed that the staged-combustion cycle offered the highest impulse and payload capability, NASA awarded parallel contracts (NAS3-16750 and NAS3-16751) to accomplish engine preliminary designs. This effort identified specific component technology needs and provided engine configurations on which to conduct control and engine dynamics studies. Component technology development and demonstration programs were initiated in 1973, and include the high-pressure hydrogen turbopump (NAS3-17794), high-pressure oxygen turbopump (NAS3-17800), thrust chamber assembly (NAS3-17825), and the preburner (NAS3-19713). These programs are in various stages of design, fabrication, and/or test and logically lead to a system demonstration of a breadboard assembly. This program was concerned with (1) the selection and preliminary design of the additional components necessary in such a system and (2) the integration of the components into a powerhead breadboard assembly (PBA) preliminary design.

The PBA effort was divided into two technical tasks, Preliminary Design and Cycle Studies, which ran concurrently, plus a reporting task. A baseline PBA was defined and used as a point of departure for the preliminary design and cycle study effort. The baseline PBA consists of the components from the technology development and demonstration programs noted above plus an oxygen heat exchanger, interconnecting lines and control valves.

Task I involved the preliminary design of the oxygen heat exchanger, interconnecting lines, and control valves as well as the preliminary design of the PBA. Task II provided for the cycle studies necessary to support the preliminary design selection process, such as establishing minimum valve requirements, and locating the oxygen heat exchanger. The cycle study effort required that the PBA system be simulated on a digital computer to provide capability for transient and steady-state analyses. An existing rocket engine computer program was used.

STUDY OBJECTIVES

The objective of this study was to accomplish the preliminary design of a Powerhead Breadboard Assembly (PBA) of major components of an 88 964-Newton (20,000 pound) thrust hydrogen/oxygen staged-combustion cycle engine. This Powerhead Breadboard Assembly (PBA) consists of an existing thrust chamber assembly, preburner, igniters, hydrogen turbopump, and oxygen turbopump combined with an oxygen heat exchanger, control valves, and interconnecting lines designed during the study. Basic requirements and operating conditions for the PBA are listed in Table 3 and Fig. 3. Turbopumps are shown in Fig. 4 with design characteristics presented in Table 4. The thrust chamber (Fig. 5) nominal design conditions are listed in Table 5. The preburner and igniter (Fig. 6) design parameters are shown in Table 6 and 7.

TABLE 3. ADVANCED SPACE ENGINE REQUIREMENTS AND OPERATING CONDITIONS

Propellants	Liquid Hydrogen (MIL-P-27201) Liquid Oxygen (MIL-P-25508)
Vacuum Thrust, Newtons (pounds)	88 964 (20,000)*
Engine Mixture Ratio	6.0 (nominal at full thrust) 5.5 to 6.5 (operating range at full thrust)
Chamber Pressure, kPa (psia)	13 789 (2000)
Propellant Inlet Temperature, K (R)	
Hydrogen Boost Pump	20.3 to 22.2 (36.5 to 40)
Oxygen Boost Pump	90 to 95.5 (162 to 172)
NPSH at Boost Pump Inlet, meters (feet)	
Hydrogen	4.572 (15) at full thrust
Oxygen	0.610 (2) at full thrust
Engine Temperature at Prestart, K (R)	111 to 311 (200 to 560)
Service Life Between Overhauls	300 thermal cycles or 10 hours accumulated run time**
Service-Free Life	60 thermal cycles or 10 hours accumulated run time**
Maximum Single Run Duration, seconds	2000
Tank Pressurant at Full Thrust, kg/s (lb/sec)	
Oxygen	0.660 (0.134) at 235 K (423 R)
Hydrogen	0.015 (0.034) at 265 K (478 R)
Tank Pressurant at Pumped Idle, kg/s (lb/sec)	
Oxygen	0.041 (0.090) at 143 K (258 R)
Hydrogen	0.005 8 (0.013) at 302.2 K (544 R)

*The engine shall also be capable of operation at tank-head idle and pumped idle. Thrust and mixture ratio magnitudes for these modes of operation shall be selected during the contract.
**A thermal cycle is defined as an engine start to any thrust level and shutdown.

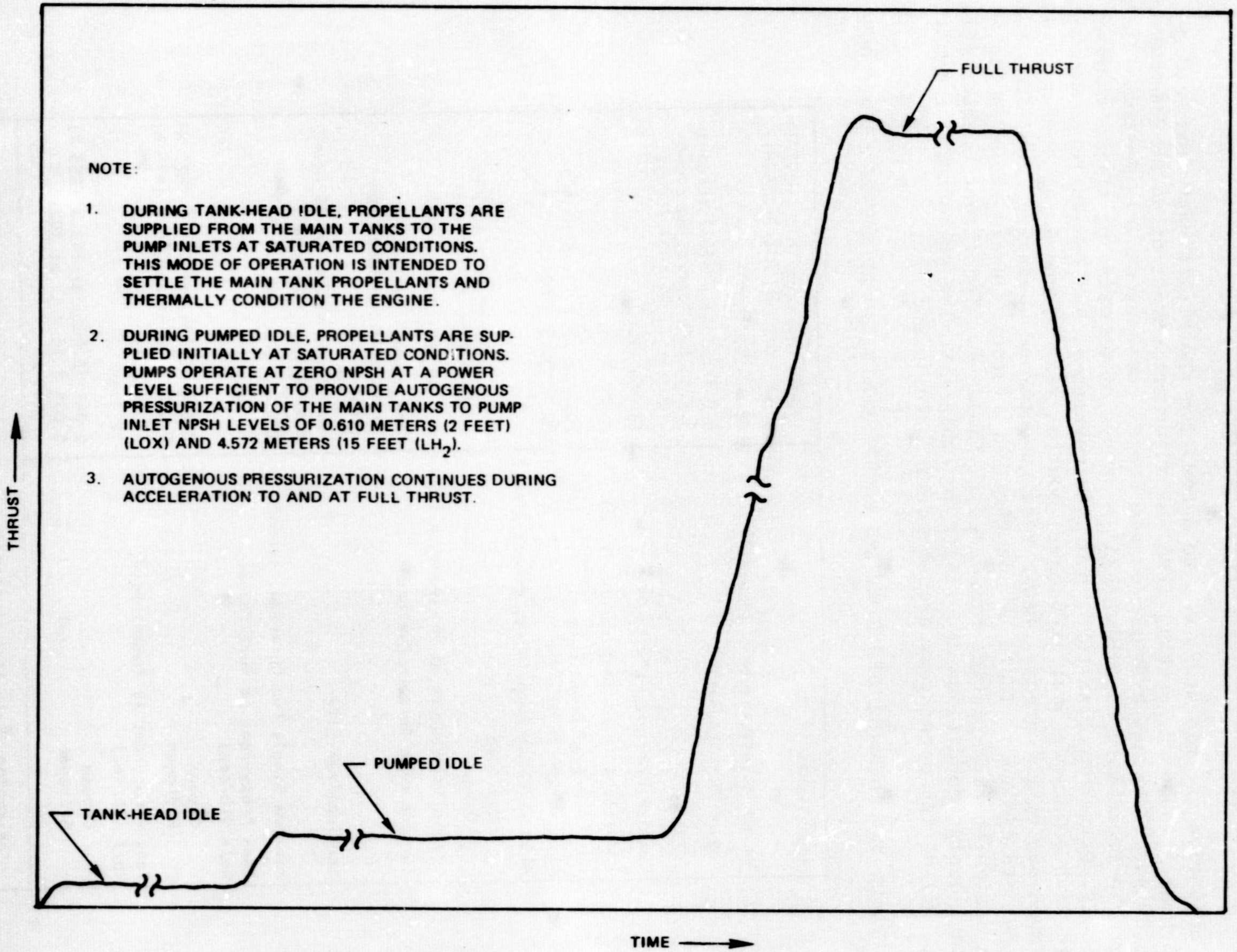
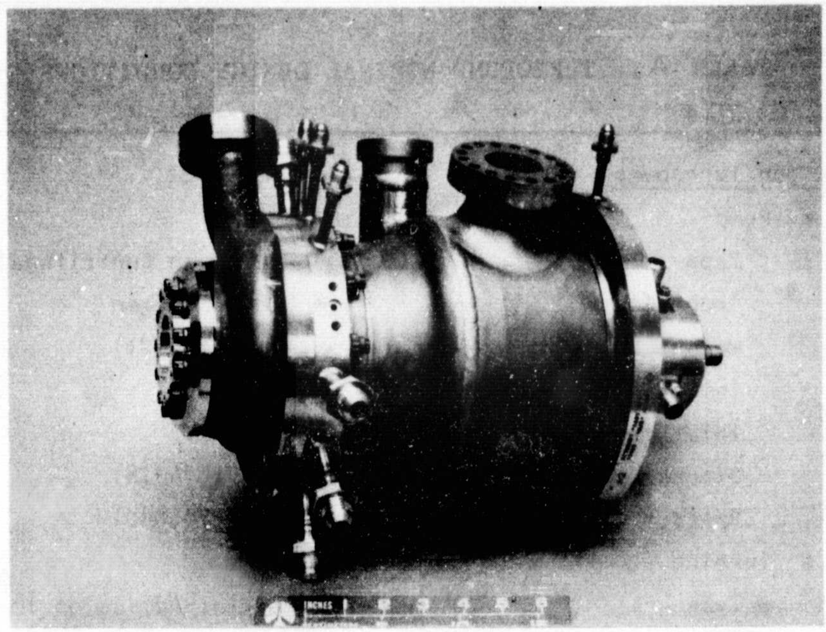


Figure 3. Advanced Space Engine Operating Conditions



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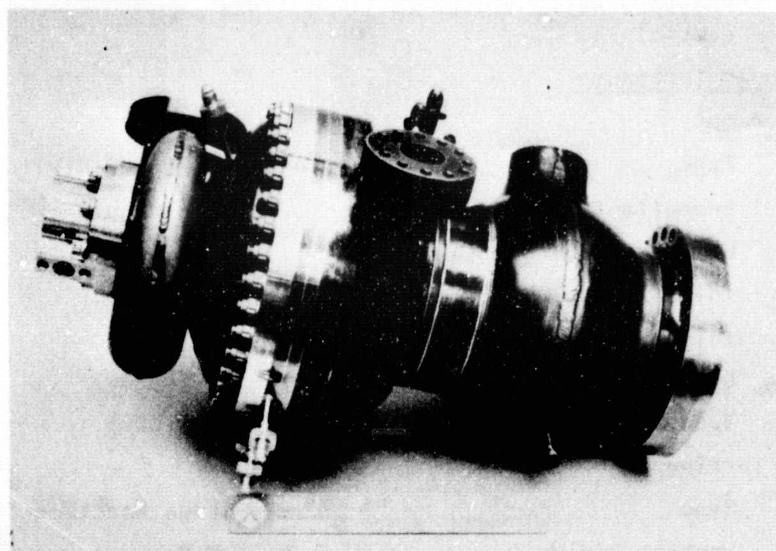
A. LIQUID OXYGEN PUMP



B. LIQUID HYDROGEN PUMP

Figure 4. Mark 48 Turbopumps

TABLE 4. TURBOPUMP NOMINAL DESIGN CONDITIONS

Oxygen Turbopump	
• Pump	
Type	One-Stage Centrifugal
Propellant	Liquid Oxygen
Weight Flow, Kg/s (lb/sec)	16.42 (36.21)
Inlet Pressure, kPa (psia)	689 (100)
Inlet Temperature, K (R)	93 (167)
Discharge Pressure, kPa (psia)	29 771 (4318)
Speed, Hz (rpm)	1167 (70,000)
• Turbine	
Type	Partial-Admission Impulse
Working Fluid	$H_2 + H_2O$
Weight Flow, Kg/s (lb/sec)	1.32 (2.92)
Inlet Pressure, kPa (psia)	23 208 (3366)
Inlet Temperature, K (R)	1041 (1874)
Pressure Ratio (total to static)	1.424
Hydrogen Turbopump	
• Pump	
Type	Three-Stage Centrifugal
Propellant	Liquid Hydrogen
Weight Flow, Kg/s (lb/sec)	2.74 (6.04)
Inlet Pressure, kPa (psia)	489 (71)
Inlet Temperature, K (R)	21 (38)
Discharge Pressure, kPa (psia)	31 440 (4560)
Speed, Hz (rpm)	1583 (95,000)
• Turbine	
Type	Two-Stage Reaction
Working Fluid	$H_2 + H_2O$
Weight Flow, Kg/s (lb/sec)	2.94 (6.48)
Inlet Pressure, kPa (psia)	23 208 (3366)
Inlet Temperature, K (R)	1041 (1874)
Pressure Ratio (total to static)	1.424

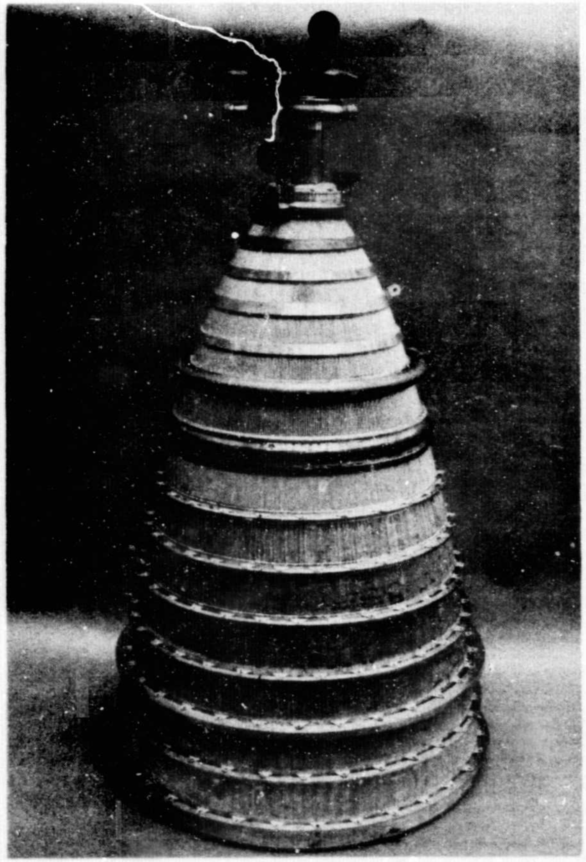


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Figure 5. ASE Thrust Chamber Assembly

TABLE 5. THRUST CHAMBER ASSEMBLY

NOMINAL DESIGN CONDITIONS

Injector	
Oxygen Inlet Pressure, kPa (psia)	20 891 (3030)
Oxygen Inlet Temperature, K (R)	108 (195)
Oxygen Weight Flow, Kg/s (lb/sec)	14.50 (31.96)
Fuel (H_2 + H_2O) Inlet Pressure, kPa (psia)	16 141 (2341)
Fuel (H_2 + H_2O) Inlet Temperature, K (R)	986 (1775)
Fuel (H_2 + H_2O) Weight Flow, (lb/sec)	4.26 (9.40)
Injector Face Coolant (hydrogen)	
Inlet Pressure, kPa (psia)	25 924 (3760)
Inlet Temperature, K (R)	237 (426)
Weight Flow, Kg/s (lb/sec)	0.150 (0.33)
Combustion Chamber	
Pressure, kPa (psia)	13 790 (2000)
Temperature, K (R)	3651 (6572)
Weight Flow, Kg/s (lb/sec)	18.91 (41.69)
Hydrogen Cooling Circuits	
Thrust Chamber (injector face to 8:1)	
Inlet Pressure, kPa (psia)	29 696 (4307)
Inlet Temperature, K (R)	50 (90)
Exit Pressure, kPa (psia)	25 966 (3766)
Exit Temperature, K (R)	223 (401)
Weight Flow, Kg/s (lb/sec)	1.98 (4.36)
Regeneratively Cooled Nozzle (8:1 to 175:1)	
Inlet Pressure, kPa (psia)	31 412 (4556)
Inlet Temperature, k (R)	50 (90)
Exit Pressure, kPa (psia)	31 171 (4521)
Exit Temperature, K (R)	489 (881)
Weight Flow, Kg/s (lb/sec)	0.59 (1.30)
Dump Cooled Nozzle (175:1 to 400:1)	
Inlet Pressure, kPa (psia)	1206 (175)
Inlet Temperature, K (R)	50 (90)
Dump Nozzle Inlet Pressure, kPa (psia)	1196 (173.4)
Dump Nozzle Inlet Temperature, K (R)	1033 (1859)
Weight Flow, Kg/s (lb/sec)	0.163 (0.36)

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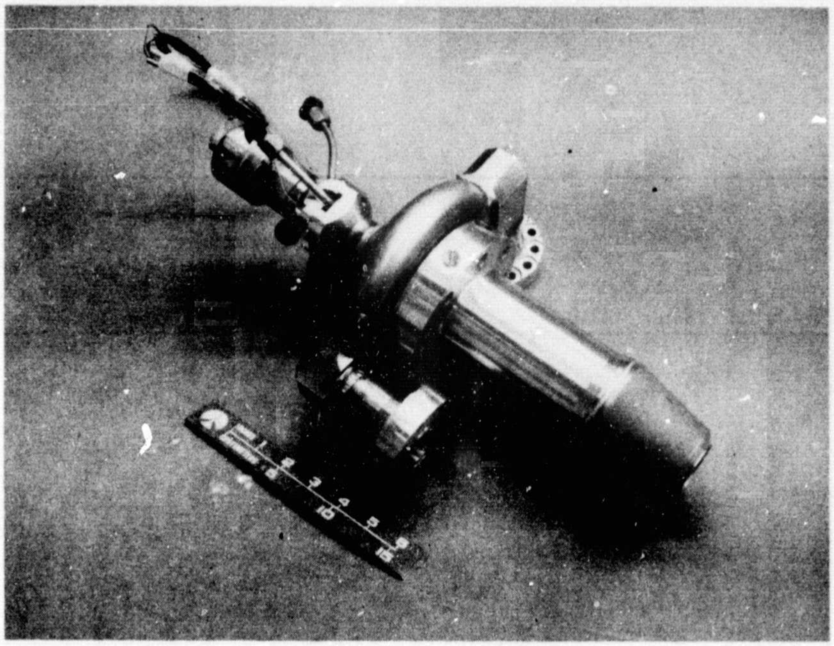

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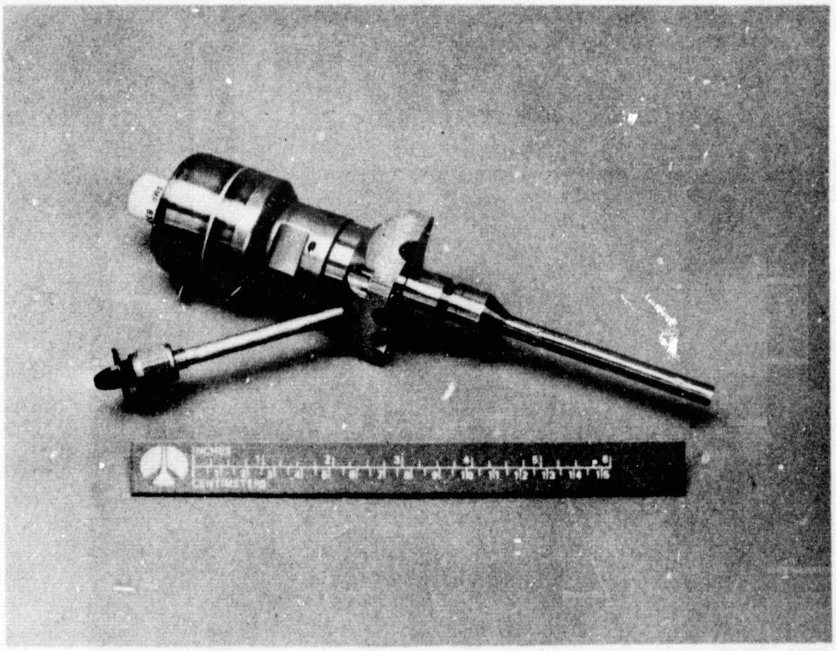

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Figure 6. ASE Preburner and Igniter Assemblies

TABLE 6. PREBURNER NOMINAL DESIGN CONDITIONS

Injector	
Oxygen Inlet Pressure, kPa (psia)	27 648 (4010)
Oxygen Inlet Temperature, K (R)	108 (195)
Oxygen Weight Flow, Kg/s (lb/sec)	1.86 (4.09)
Hydrogen Inlet Pressure, kPa (psia)	25 924 (3760)
Hydrogen Inlet Temperature, K (R)	237 (426)
Hydrogen Weight Flow, Kg/s (lb/sec)	2.41 (5.31)
Combustion Chamber	
Pressure, kPa (psia)	23 345 (3386)
Temperature, K (R)	1042 (1876)
Weight Flow, Kg/s (lb/sec)	4.26 (9.40)

TABLE 7. IGNITER NOMINAL DESIGN CONDITIONS

Oxygen Inlet Pressure, kPa (psia)	29 750 (4315)
Oxygen Inlet Temperature, K (R)	235 (423)
Oxygen Weight Flow, Kg/s (lb/sec)	0.0206 (0.0455)
Hydrogen Inlet Pressure, kPa (psia)	25 924 (3760)
Hydrogen Inlet Temperature, K (R)	265.6 (478)
Hydrogen Weight Flow, Kg/s (lb/sec)	10 251 (0.0555)
Core Mixture Ratio	40:1
Spark Igniter Voltage, volts	24
Spark Igniter Current, ampere	1

BASELINE PBA CONFIGURATION

The baseline PBA as defined at the start of the study, is controlled with 12 valves shown in Fig. 7 and functionally described below:

- Facility Valves are located at the inlets to the pumps to provide shutoff of the propellants when the PBA is not operating.

- The Fuel Cavitation Venturi is located downstream of the hydrogen pump and controls hydrogen flow into the cooling jackets. During pumped idle the valve is scheduled to induce cavitation at the venturi throat to provide isolation of the hydrogen pump from possible instability in the cooling jackets.

- The Main Chamber Oxidizer Valve is located downstream of the oxygen pump in the line to the thrust chamber and controls oxygen flow to the main combustion chamber. During tank head idle the valve is closed to divert all of the oxygen to the oxygen heat exchanger.

- The Preburner Oxidizer Valve is located downstream of the oxygen pump in the line to the preburner and controls oxygen flow to the preburner combustion chamber. During tank head idle and pumped idle the valve is closed to prevent oxygen flow to the preburner.

- The Fuel Bypass Valve is located downstream of the hydrogen pump and allows a portion of the hydrogen to bypass the cooling jackets, preburner, and turbines during tank head idle.

- The Fuel Shunt Valve is located in the hydrogen line downstream of the combustion chamber cooling jacket and controls the amount of hydrogen bypassed to the oxygen heat exchanger.

- The Gaseous Oxygen Control Valve is located downstream of the oxygen heat exchanger and controls gaseous oxygen flow to the vehicle tank and to the main combustion chamber.

- Igniter Valves (4) are used to control oxygen and hydrogen flow to the preburner and main combustion chamber igniters. During tank head idle and pumped idle the preburner igniter valves are closed to prevent propellant flow to the preburner igniter.

In this configuration, the PBA is capable of operating in three propulsive modes:

1. Tank head idle to thermally condition PBA hardware for intiation of subsequent propulsive phases

2. Pumped idle to provide GH_2 and GO_2 pressurants to the propellant tanks prior to start of full-thrust mode

3. Full-thrust mode at mixture ratios between 5.5 and 6.5

In the tank head idle mode, the saturated propellants are used to thermally condition the engine hardware and still provide propulsive force by main chamber combustion at a low level. Fuel enters the chamber both through the cooling jacket and via a bypass route through the fuel turbopump to more rapidly chill the turbopump. A small amount of oxidizer is passed through a heat exchanger and around the main oxidizer valve into the main combustion chamber. The fuel shunt valve is positioned to provide warm fuel to the heat exchanger to gasify the oxygen.

After the hardware is thermally conditioned, for transition to the pumped idle mode, the fuel bypass valve is closed to force all fuel through the cooling jacket and provide turbine drive fluid for boost turbopumps.* The fuel shunt valve is positioned to allow fuel to bypass the heat exchanger. The gaseous oxidizer valve is positioned to pressurize the oxidizer tank and the main chamber oxidizer valve is set to provide LOX to the main chamber.

After the tanks have been pressurized to provide the required NPSH at the pump inlets, the preburner igniter valves and oxidizer valve are opened to provide preburner power to the turbopumps for transition to the full-thrust mode.

After transition to full thrust, the preburner oxidizer and main oxidizer valves are placed into their control modes to provide thrust and mixture ratio control.

*(Boost turbopumps are not included in the PBA. The pressure drop is simulated with an orifice).

CYCLE STUDIES

Cycle studies were initiated on the baseline PBA schematic as shown in Fig. 7. The existing mathematical model was compared to test information on thrust chamber heat transfer and pump performance such as turbine and pump efficiencies and pump H-Q mapping information contained in NASA reports CR-135186 and CR-135211 on the liquid fuel and oxidizer pumps, respectively. Data from the fuel pump testing shows agreement at the lower speeds with the theoretical information already contained in the model. The early data on the oxidizer pump showed low performance at higher speeds and the theoretical data was retained in the model. Subsequent oxidizer pump modification and testing showed agreement with the theoretical curves retained in the model. The heat exchanger and new valves were added and preliminary engine balances were made at tank head idle, powered idle and mainstage conditions. To ensure that sufficient energy would be available to drive the low-pressure pumps in the final flight configuration, an orifice was included in the PBA model to simulate the energy requirements of the low-pressure pump turbines. To avoid excessive computer run time costs, the turbopumps were assumed to be chilled to the pump outlet flanges for all tank head idle runs.

HEAT EXCHANGER LOCATION

Examination of the heat exchanger available operating parameters from the preliminary balances showed that at the powered idle mode conditions, the thrust chamber jacket coolant outlet temperature is only 75 K (135 R). This is obviously not sufficient to generate gaseous oxidizer at 97 K (175 R). The similar temperature at tank head idle mode is only marginally adequate at 117 K (210 R). In an attempt to improve the heat exchanger performance, the hydrogen for the heat exchanger was tapped off the thrust chamber nozzle coolant flow instead of the thrust chamber jacket coolant (Fig. 8). This provides heat exchanger temperatures of 380 K (684 R) and 652 K (1174 R) at powered idle and tank head idle conditions, respectively. Further analysis of the three fluid heat exchangers shown in Fig. 8 indicated that little benefit was derived from the preburner flow going to the oxidizer turbine. The heat exchanger was then relocated to the location in the nozzle coolant outlet line shown in Fig. 9 and converted to a two-fluid heat exchanger.

The engine mathematical model does not perform detailed design calculations on the heat exchanger. It does provide an end-to-end heat balance across the exchanger. For a more detailed design analysis of the heat exchanger, see the section entitled "LOX Heat Exchanger."

FUEL SHUNT VALVE

The fuel shunt valve which was originally located at No. 13 in Fig. 7 was relocated to No. 13 in Fig. 9. Based on analysis presented in the heat exchanger section, the valve was sized to limit the ΔP across the heat exchanger to 689 kPa (100 psia). This provides more than adequate flow through the heat exchanger while limiting the pressure drop due to the heat exchanger in the low-pressure pump turbine drive circuit.

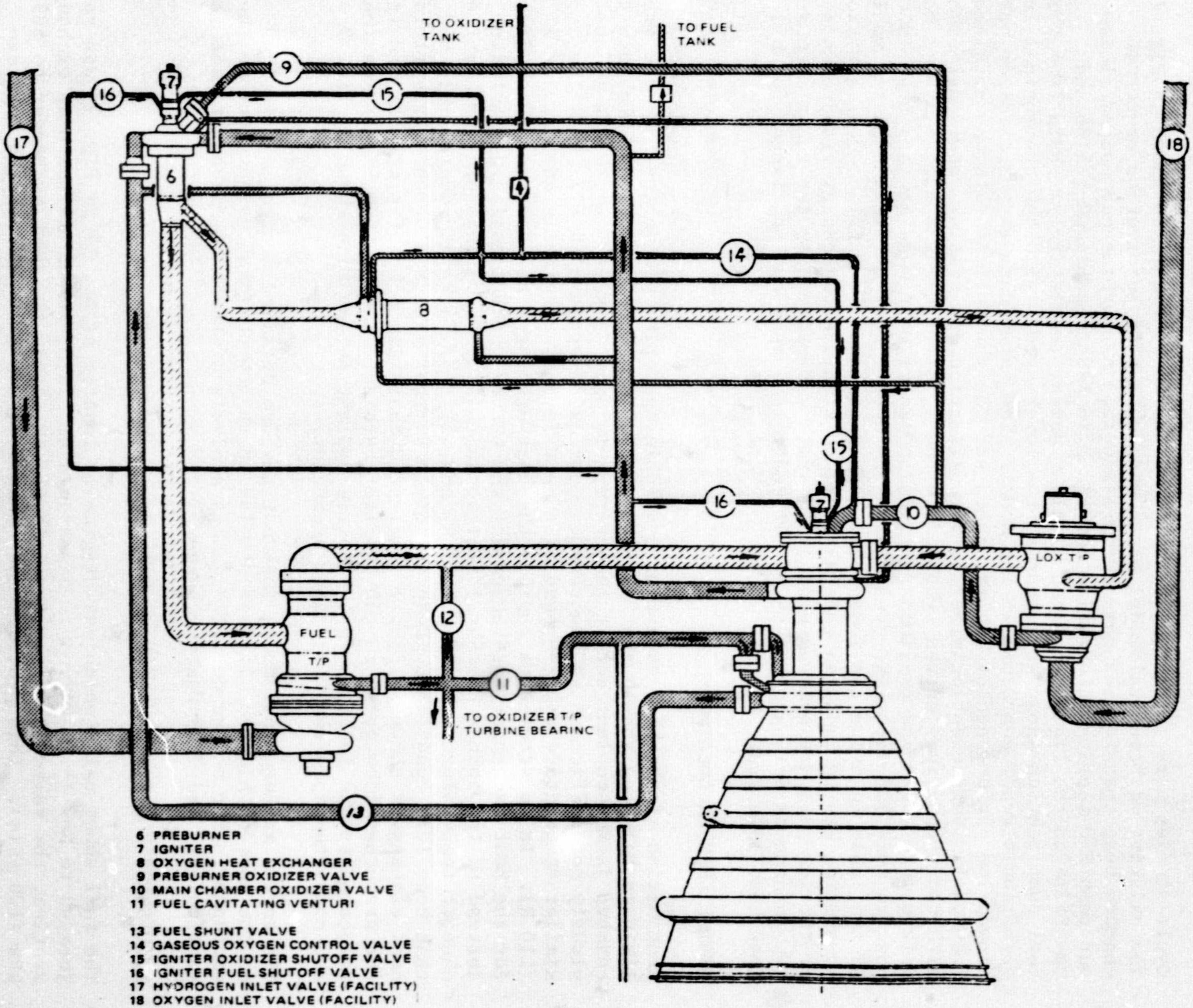

Figure 7. PBA System Baseline Design

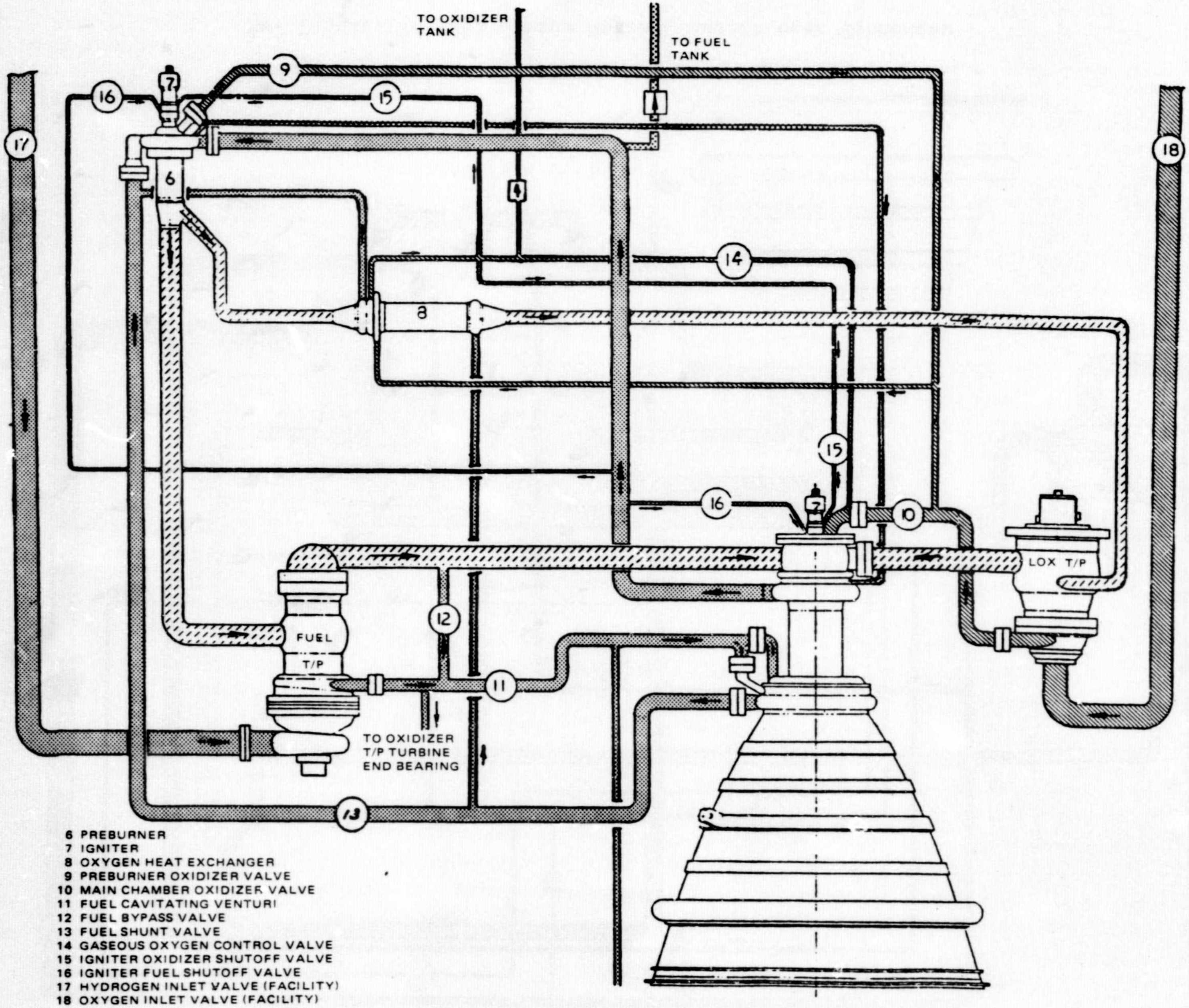

Figure 8. PBA System Nozzle Coolant Tapoff Heat Exchanger

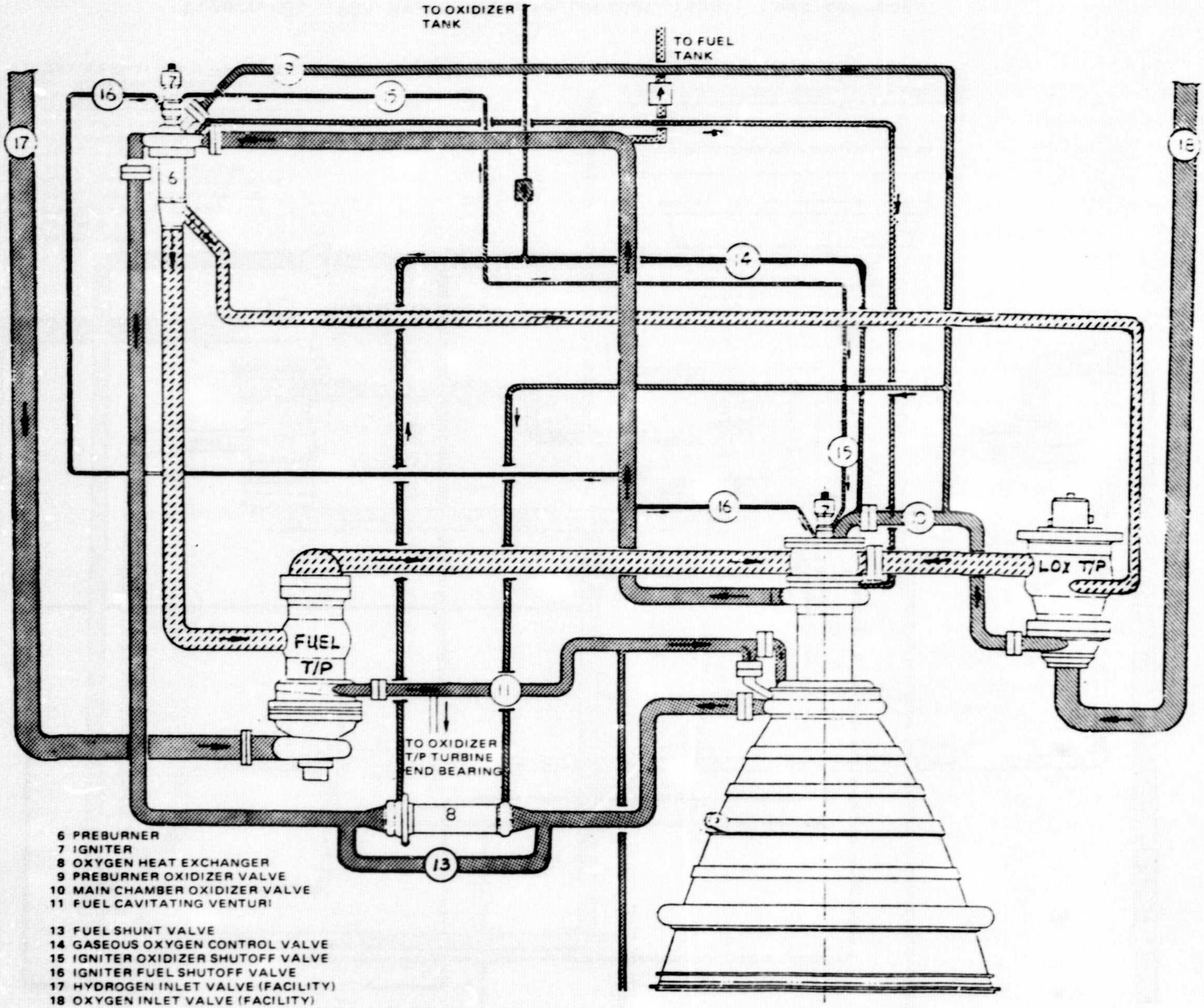

Figure 9. PBA System Nozzle Coolant Heat Exchanger

FUEL BYPASS VALVE

After relocating the heat exchanger and fuel shunt valve to the nozzle coolant line, model runs at tank head idle (THI) conditions were made to size the fuel bypass valve (No. 12 in Fig. 7). The primary purpose of the fuel bypass valve, as described inthe Statmene tof Work, is to allow more fuel flow through the turbopump during THI to chill the pump and bypass the thrust chamber resistance. It was soon apparent however, that bypassing any fuel around the thrust chamber failed to provide enough fuel to operate the heat exchanger, and the fuel bypass valve was eliminated. The fuel bypass valve also bypassed the turbopump turbine drive gas, and thus limited turbopump speed at THI conditions. If the pumps are free to rotate and the bypass valve is eliminated, the low breakaway torque of the pumps will allow them to transition to powered idle speeds of 4167 Hz (25,000 rpm) without proper chilling. Thus, the baseline tank head idle mode requires a mechanical brake on the turbopump to prevent rotation.

MAIN FUEL VALVE

The main fuel valve included in the baseline configuration contained a cavitating venturi feature to isolate the pump from possible boiling instability in the cooling jacket during pumped idle. Preliminary balances showed that the hydrogen pump discharge pressure for the pumped idle mode was sufficiently above critical pressure that boiling instability was not likely to occur. Consideration was given to deleting the valve since it is not used to control flow at mainstage. However, the valve was retained in the system in view of its possible use in an alternate tank head idle mode in which the pumps are allowed to rotate (discussed below).

Engine Balances

After relocating the heat exchanger and adjusting the fuel valves, balances were run at tank head idle (Fig. 10), powered idle (Fig. 11), and mainstage at three different mixture ratios (Fig. 12, 13, and 14). Using these balance points, cathode ray tubes (CRT's) of the transition into tank head idle mode for the locked pump case were generated and are presented in Fig. 15 through 26. Where two lines occur on the CRT, they indicate the degree of fluctuation in the parameter caused by a rapidly changing balance.

ALTERNATIVE CONFIGURATION THI

An alternative THI mode is presented in Fig. 27. For this condition, the pump rotors have been allowed to turn, and a bypass line has been inserted from the preburner to the main fuel injector to keep the pump speeds below 116 Hz (10,000 rpm) until the hardware has chilled sufficiently to allow higher speeds. The benefits of providing this bypass are:

1. For this alternative THI condition, the main fuel valve can be closed to its cavitating venturi position since sufficient pump discharge pressure is available to allow the valve ΔP and still drive the thrust chamber coolant circuit and heat exchanger. This also allows

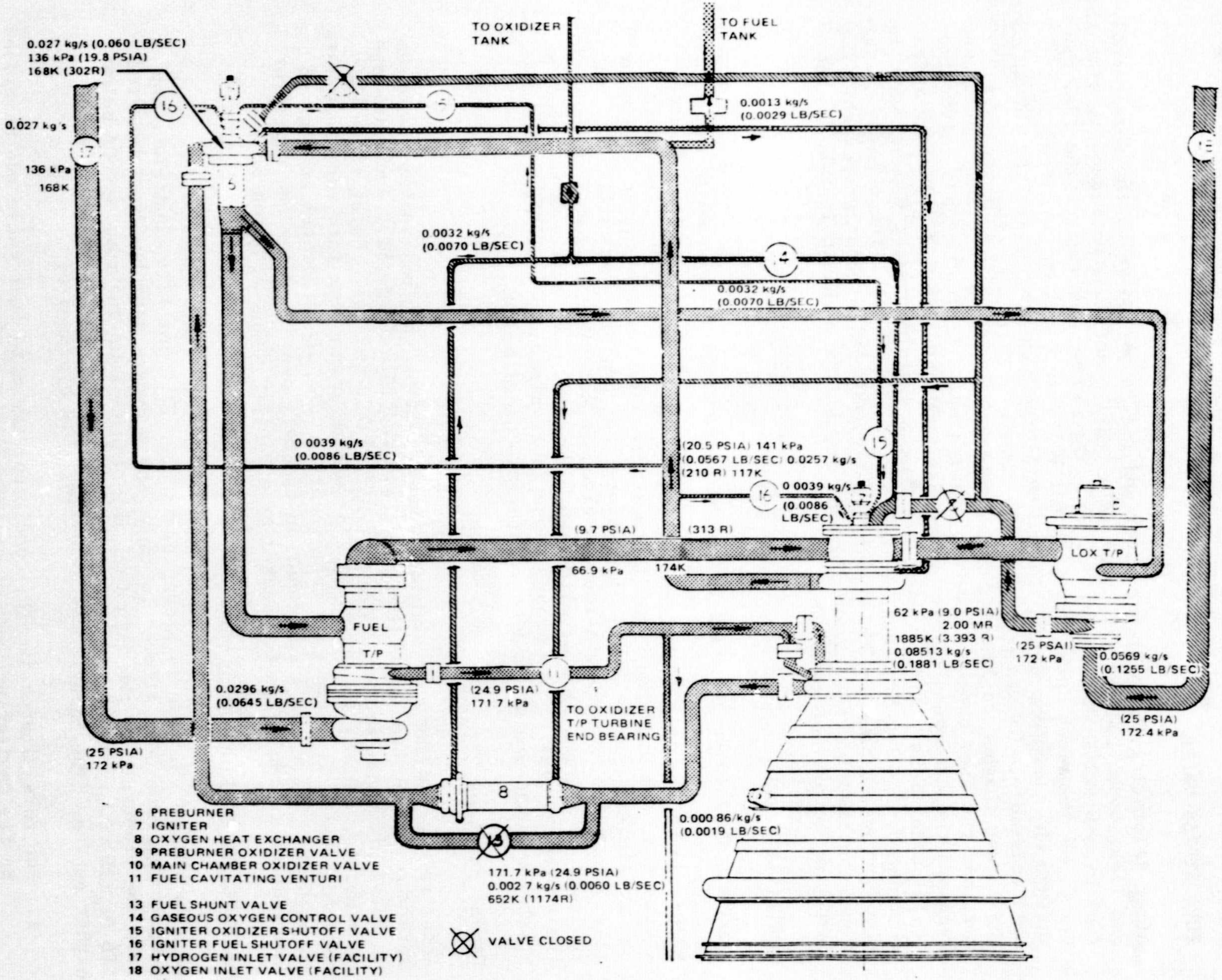

Figure 10. PBA System Tank Head Idle

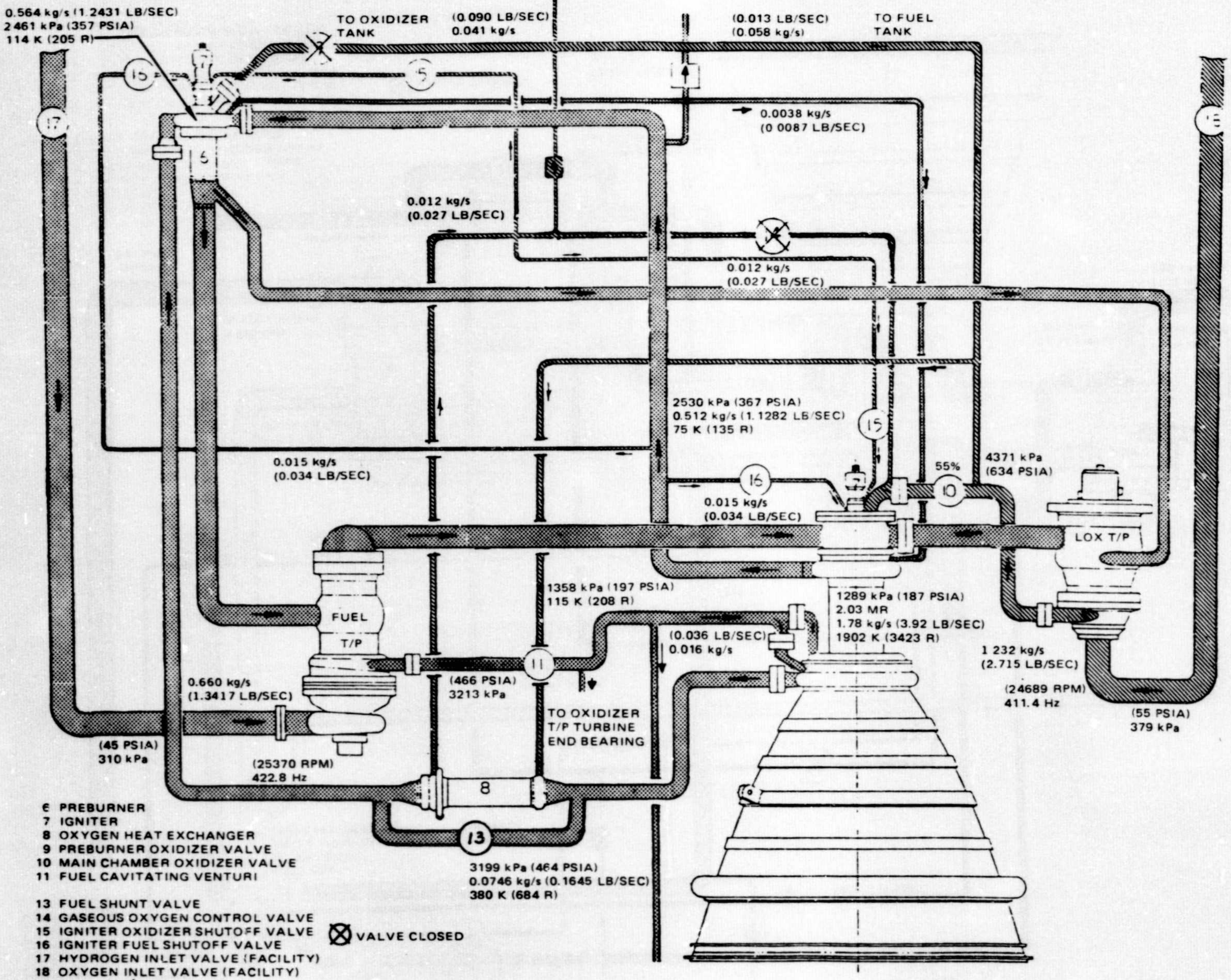

Figure 11. PBA Powered Idle Mode

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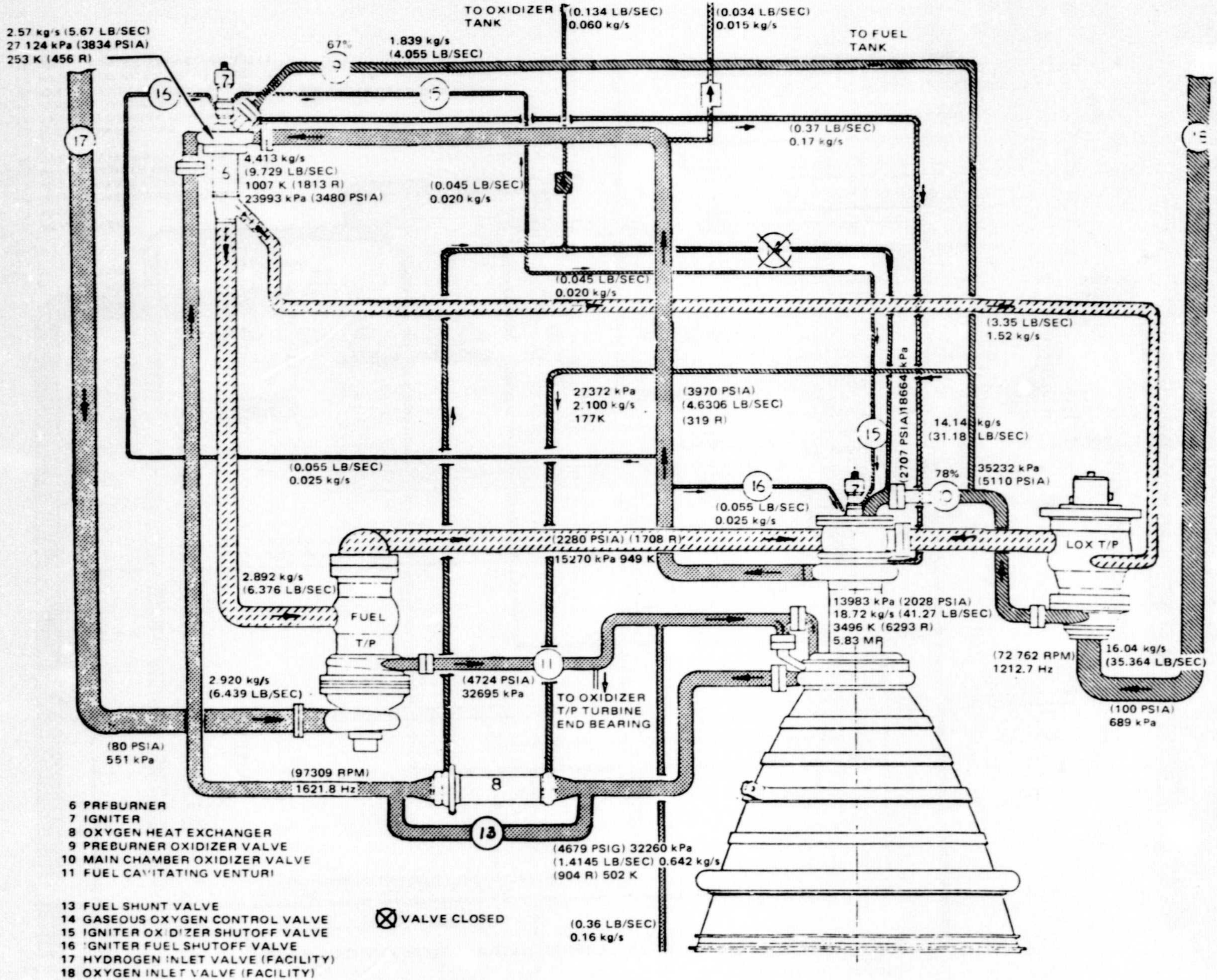

Figure 12. PBA System Mainstage (5.5 MR)

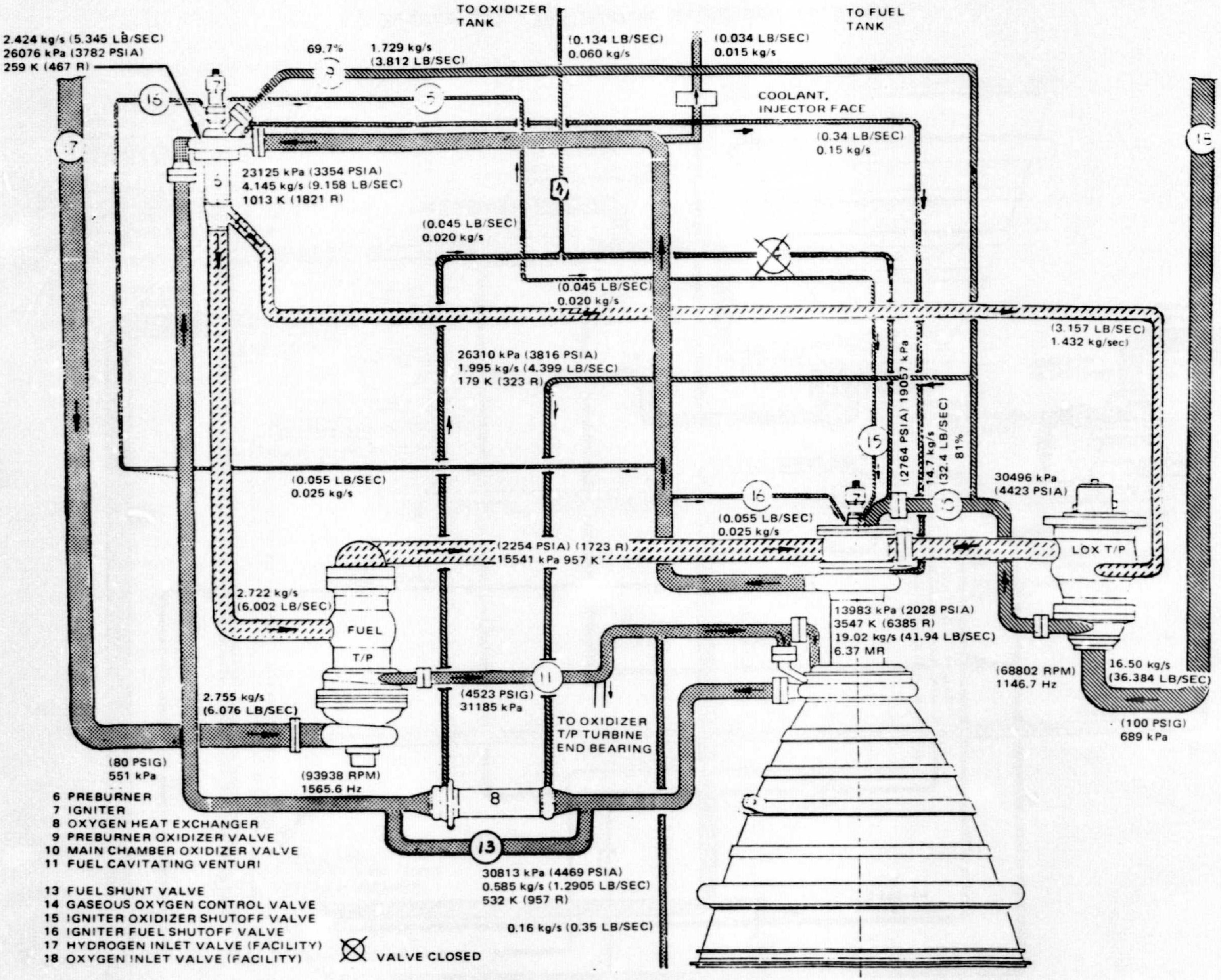

Figure 13. PBA System Mainstage (6.0 MR)

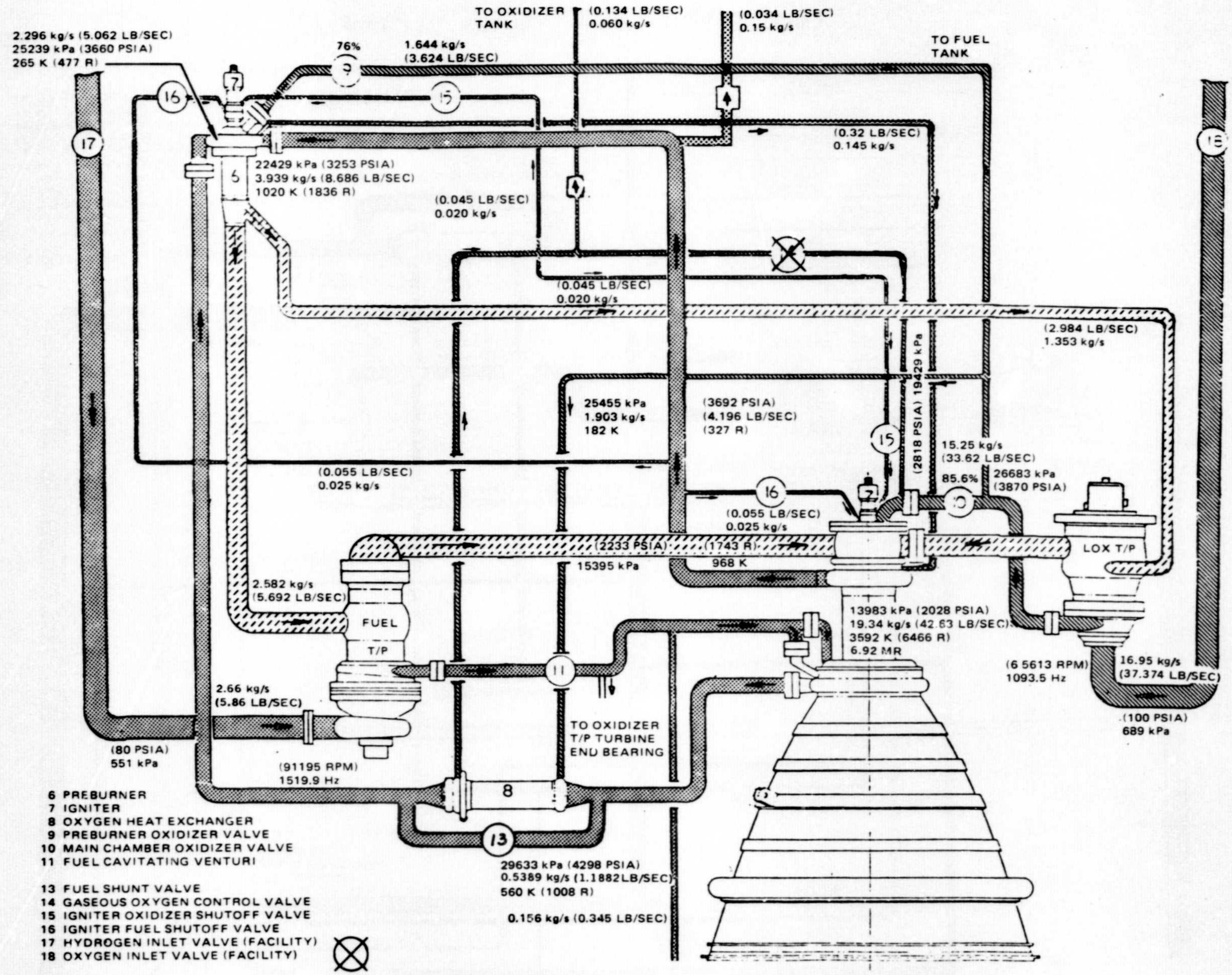

Figure 14. PBA System Mainstage (6.5 MR)

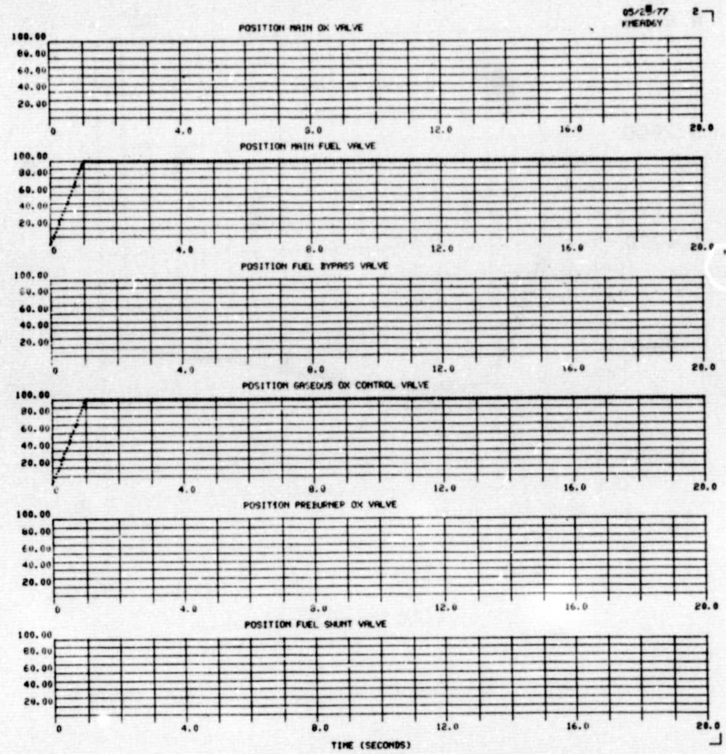

Figure 15. Valve Position vs Time (THI)

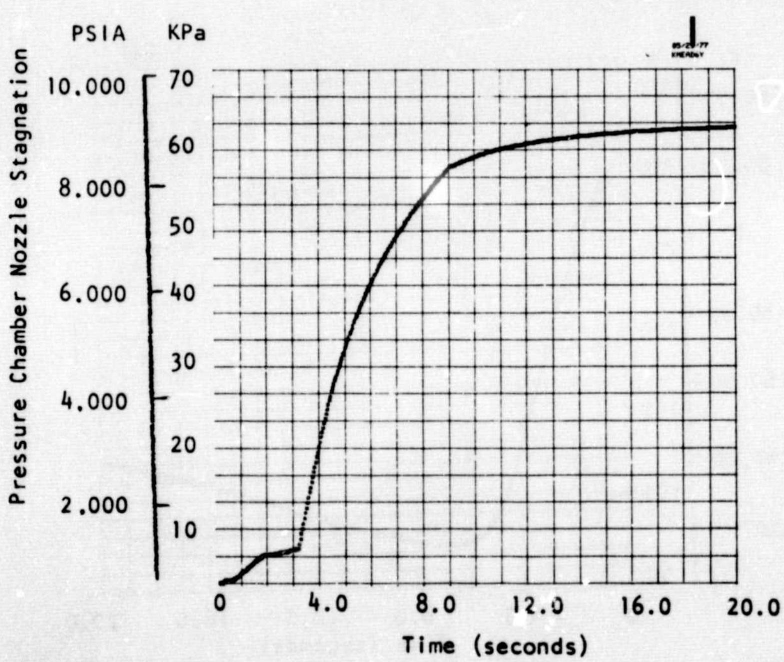

Figure 16. Chamber Pressure vs Time (THI)

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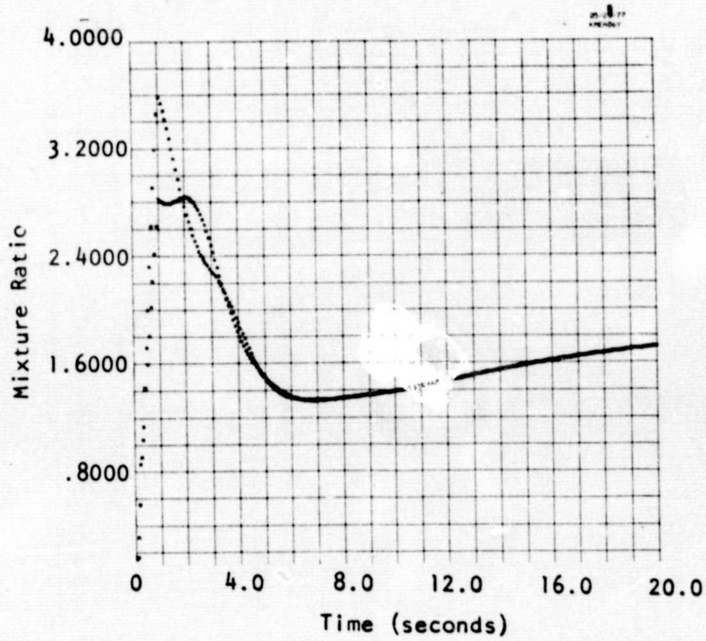

Figure 17. Mixture Ratio vs Time (THI)

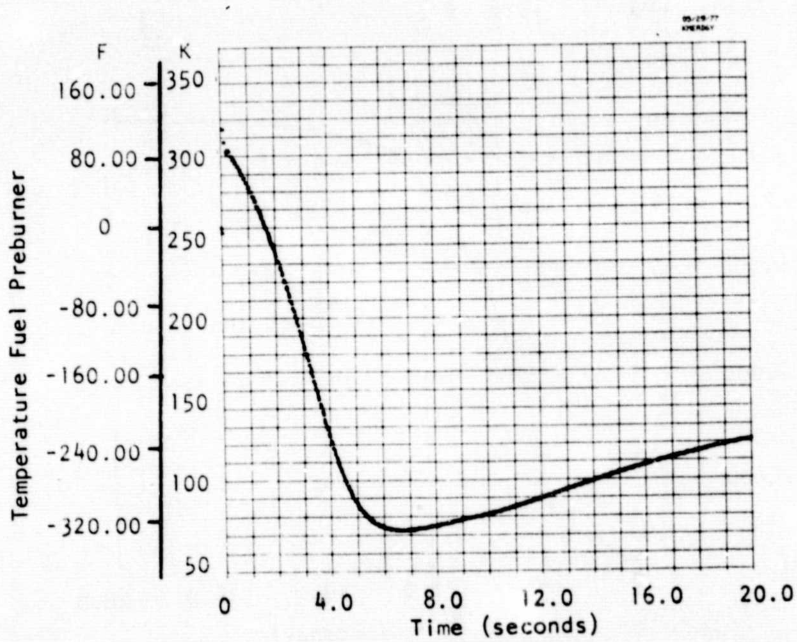

Figure 18. Fuel Preburner Temperature vs Time (THI)

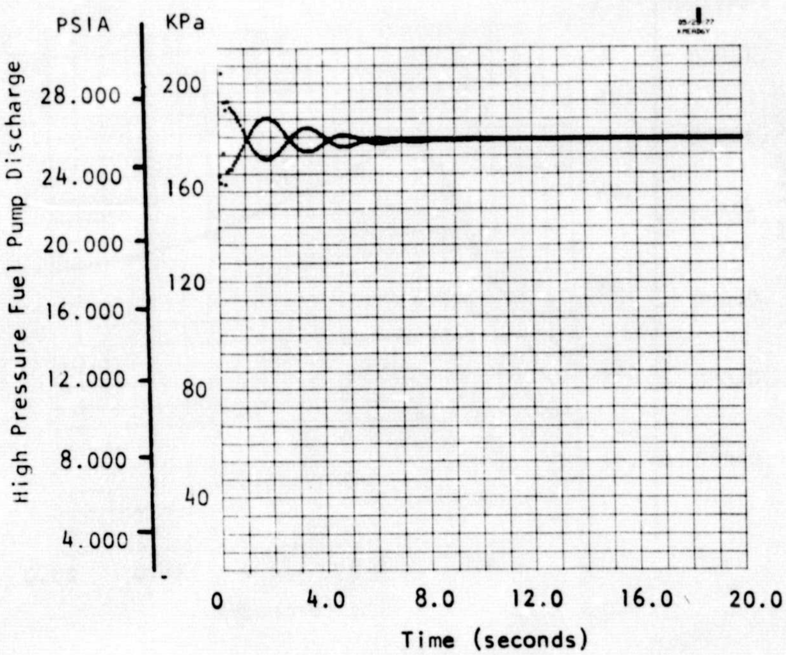

Figure 19. Fuel Pump Discharge Pressure vs Time (THI)

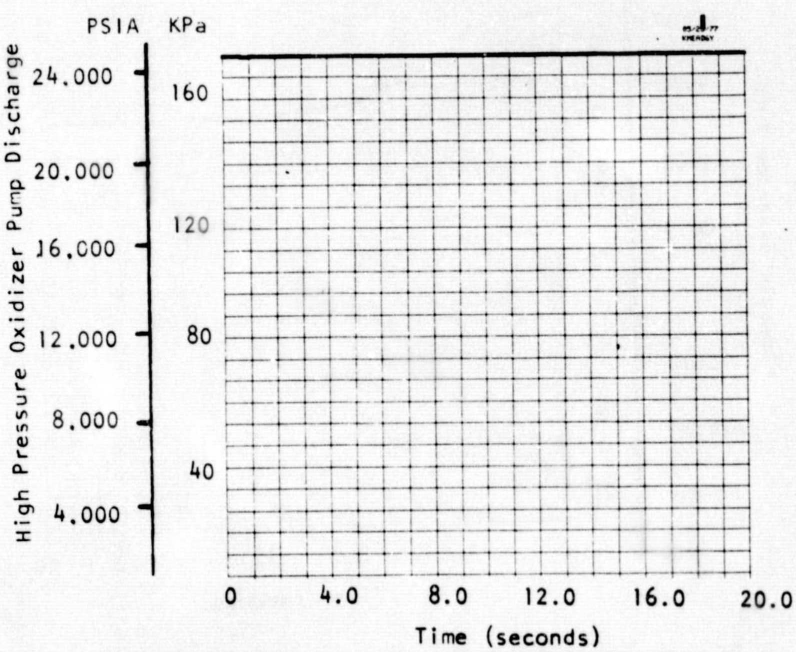

Figure 20. Oxidizer Discharge Pressure vs Time (THI)

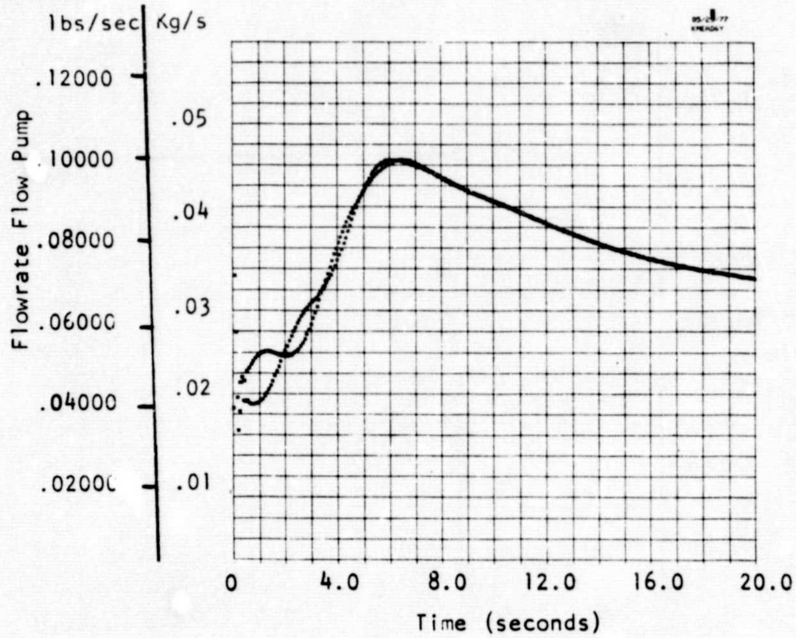

Figure 21. Fuel Pump Flowrate vs Time (THI)

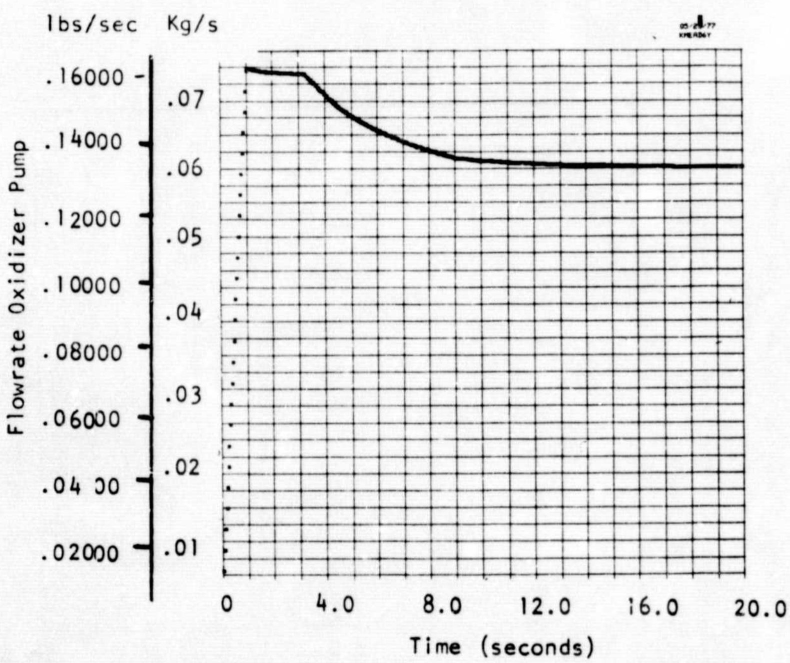

Figure 22. Oxidizer Pump Flowrate vs Time (THI)

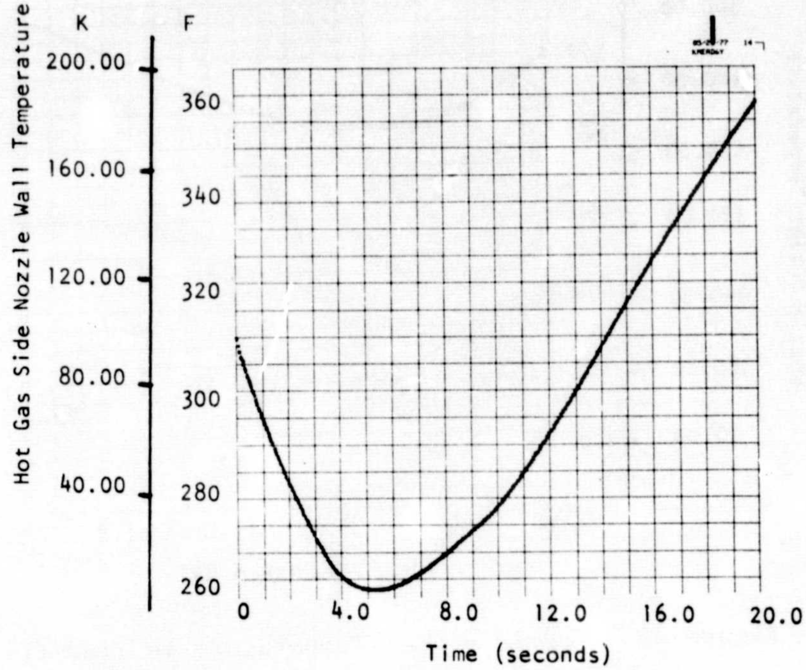

Figure 23. Hot Gas Side Nozzle Wall Temperature vs Time (THI)

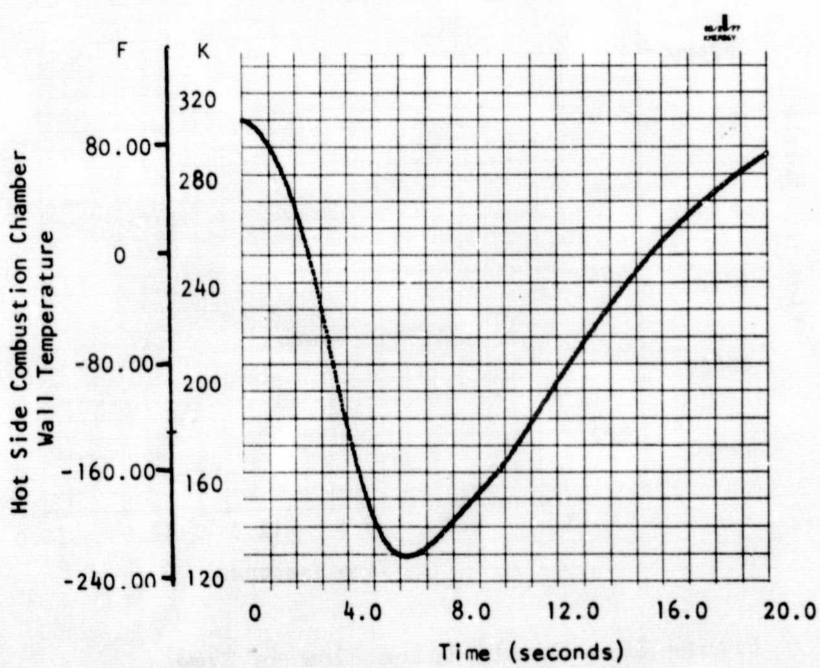

Figure 24. Hot Gas Side Combustion Chamber Wall Temperature vs Time (THI)

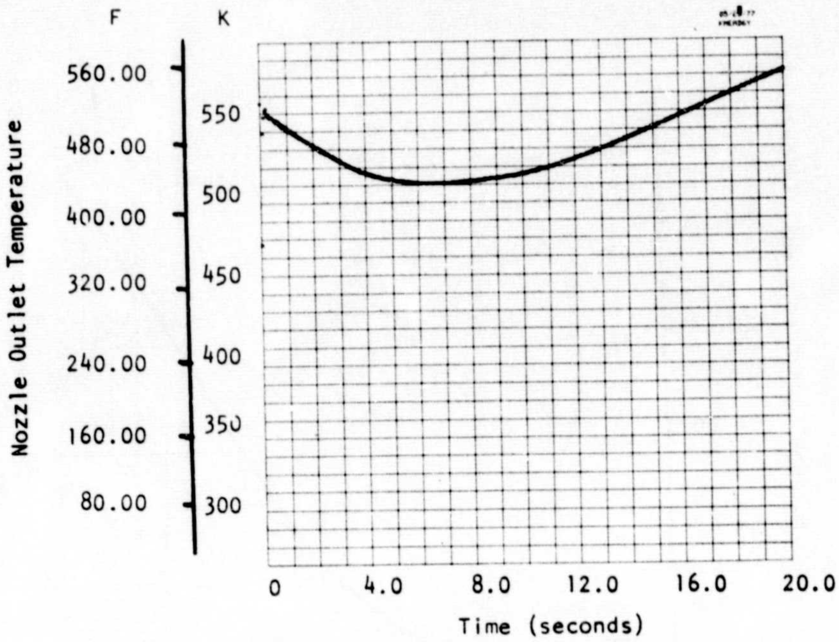

Figure 25. Nozzle Outlet Temperature vs Time (THI)

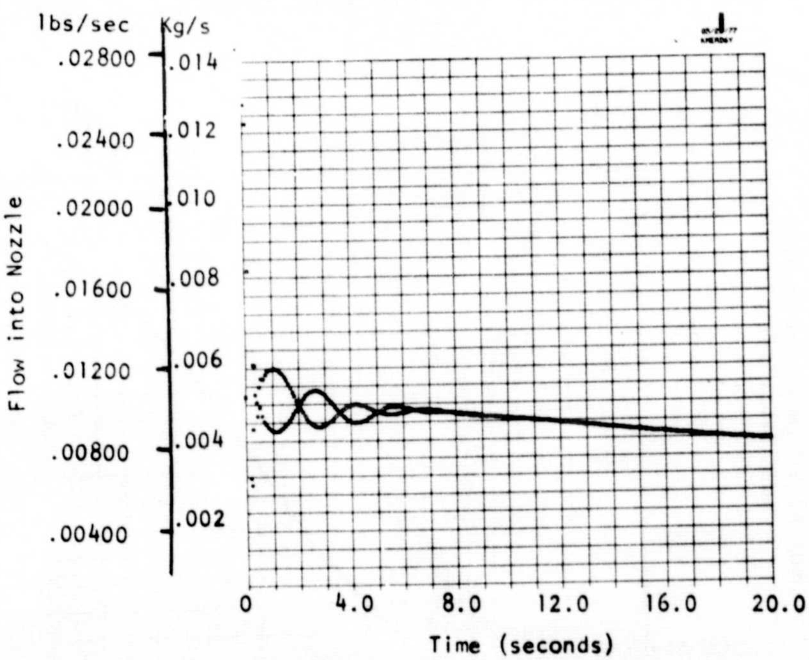

Figure 26. Nozzle Inlet Flow vs Time (THI)

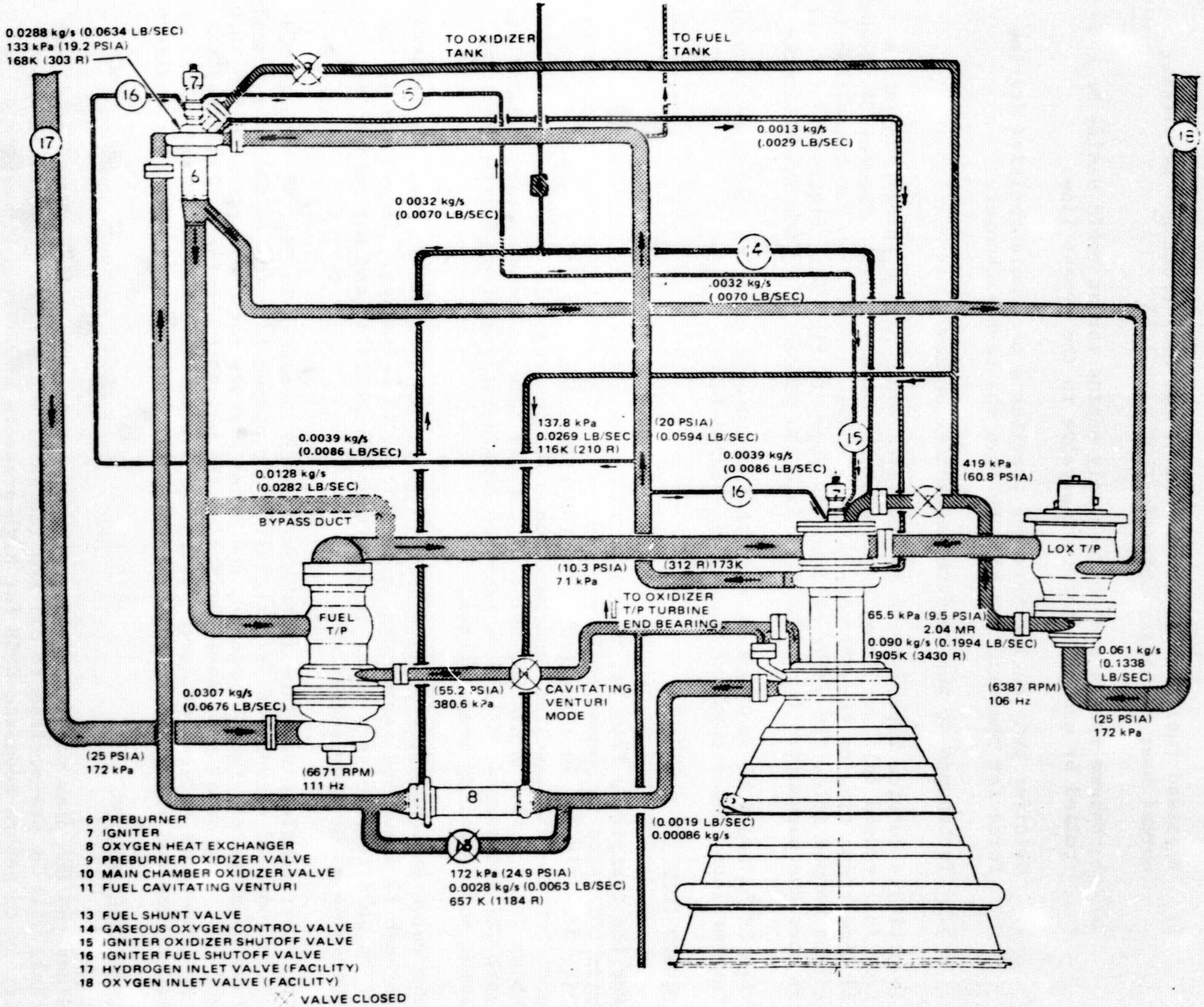

Figure 27. PBA System Tank Head Idle (alternate)

the cavitating venturi feature to isolate chamber fuel jacket flow instabilities from the turbopump. For the full-pumped idle condition, the fuel valve is then opened fully.

2. Bypassed fuel flow is downstream of the heat exchanger permitting normal heat exchanger operation.

3. Turbopump speeds and consequently engine thrust could easily be controlled by use of a throttling valve in the bypass line.

4. Oxidizer pump outlet pressure provides a much more positive driving force for the oxidizer flow through the heat exchanger.

5. Turbopumps do not require mechanical brakes.

Inserting a turbine bypass valve in this line would permit transition into a true full-pumped idle condition by closing the bypass valve. Figures 28 through 41 show transition to the THI mode balance shown in Fig. 27. For transition to a true pumped idle, the valve sequence is shown in Fig. 42. Figures 43 through 56 show the parameters for transition into the pumped idle from the alternate THI.

Then CRT's could be smoothed by a further refinement of valve timing to provide intermediate levels anywhere up to full-pumped idle.

PUMPED IDLE

For the transition from THI to pumped idle, the pump rotors are unlocked, the main LOX valve is opened to 55 percent and the GOX valve is closed as shown in Fig. 57. Figures 58 through 71 show the transition from THI to powered idle mode for the PBA baseline configuration. The powered idle mode balance is shown in Fig. 11. A mixture ratio of 2.0 was selected as the balance point for both THI and powered idle mode based on considerations of stability, performance, and operating temperatures.

The valve sequence from powered idle to mainstage is shown in Fig. 72. Figures 73 through 87 shows the parameters in transition to mainstage. In all cases, the CRT's were carried to a point to determine workability, and not refined to determine an optimum sequence.

The final complete sequence is summarized and presented in Fig. 88 through 103. It includes 20 seconds of THI, transition to pumped idle for 20 seconds, transition to mainstage for 20 seconds, and brief mixture ratio excursion to 5.5, 6.0, and 6.5. The model runs were carried to the point of showing workability, and the transients between different operational modes were not optimized. Further model runs and valve timing adjustments would result in more optimum transients.

SEA LEVEL TESTING

Since the PBA does not include low-pressure pumps, the main fuel and oxidizer tanks will be pressurized to 551 kPa (80 psia) and 689 kPa (100 psia) respectively to ensure adequate NPSH for high-pressure turbopumps at mainstage

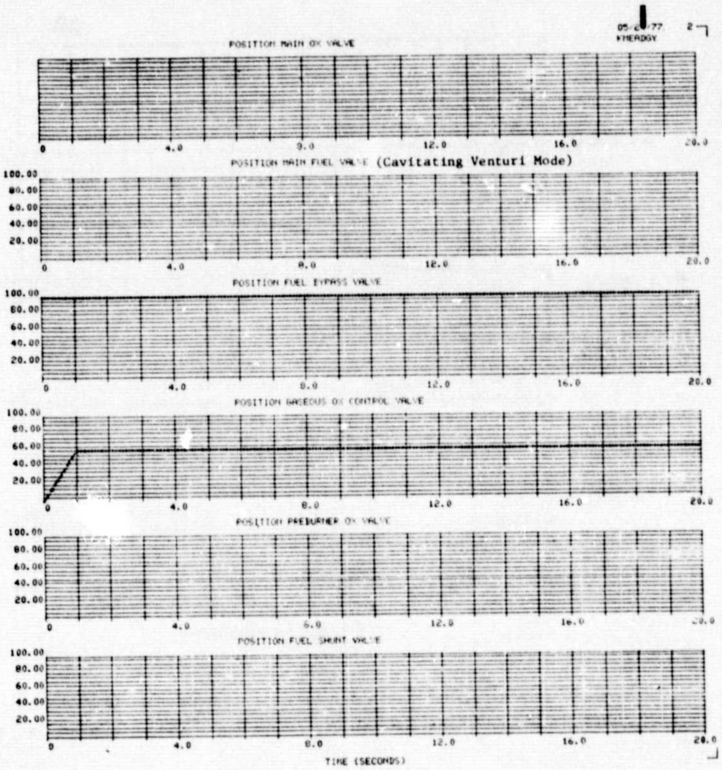

Figure 28. Valve Position vs Time (THI alt)

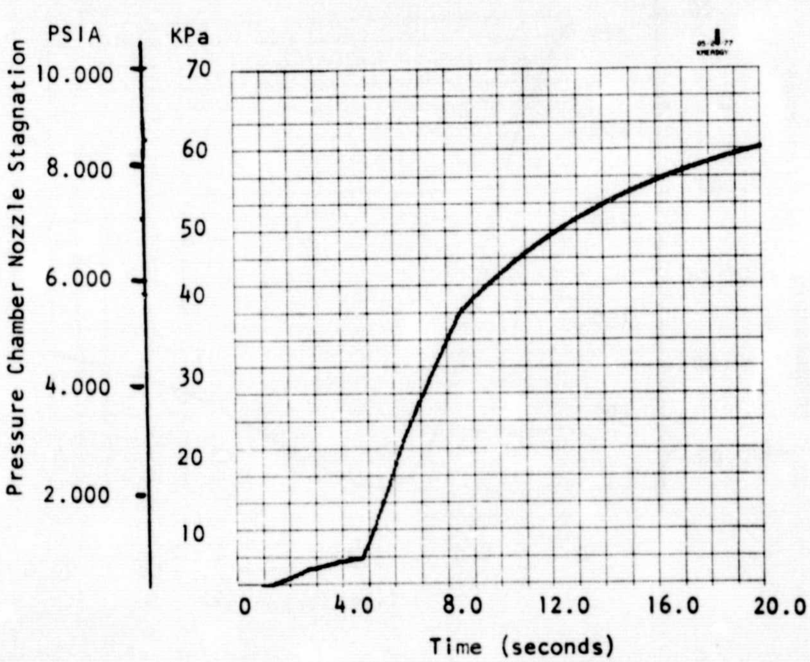

Figure 29. Chamber Pressure vs Time (THI alt)

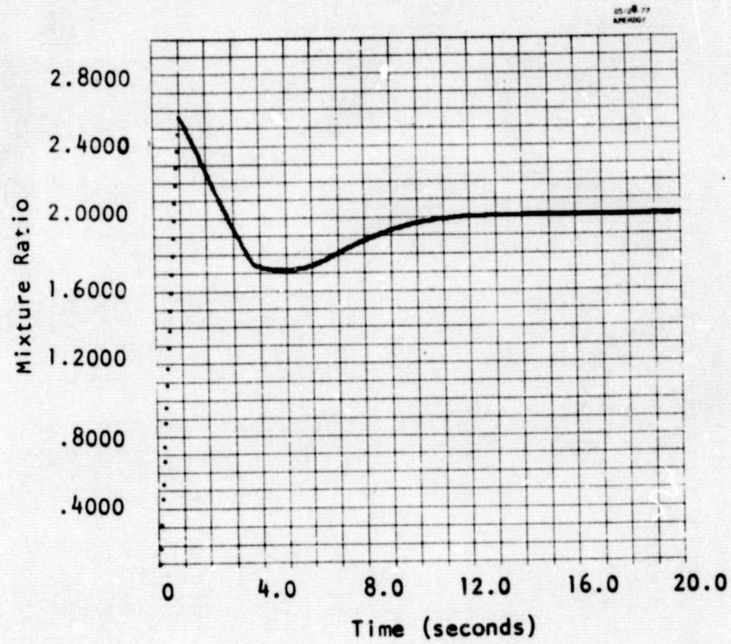

Figure 30. Mixture Ratio vs Time (THI alt)

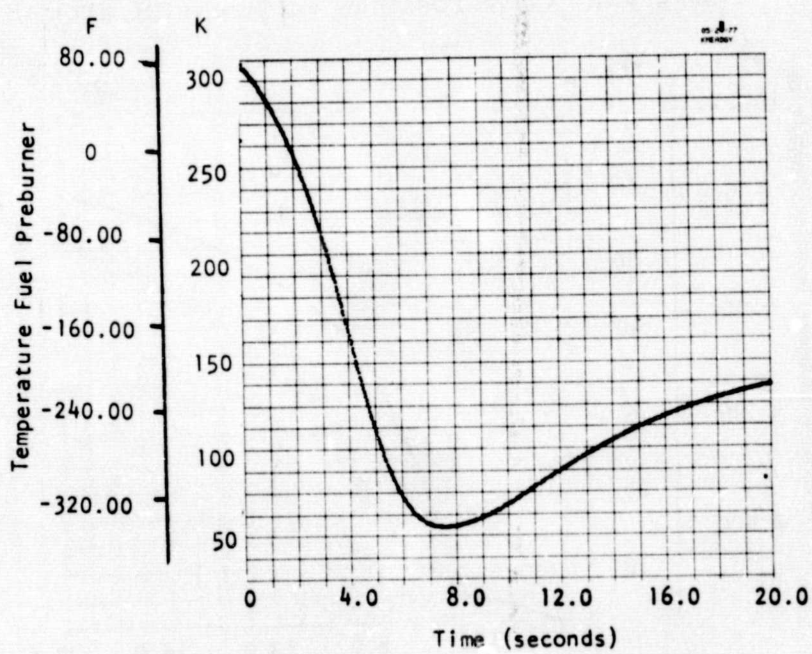

Figure 31. Preburner Fuel Temperature vs Time (THI alt)

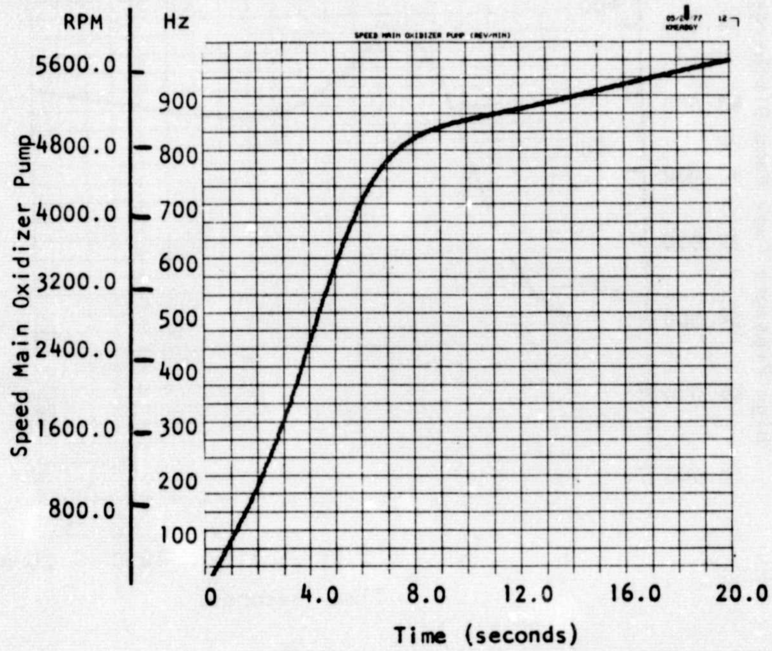

Figure 32. Oxidizer Pump Speed vs Time (THI alt)

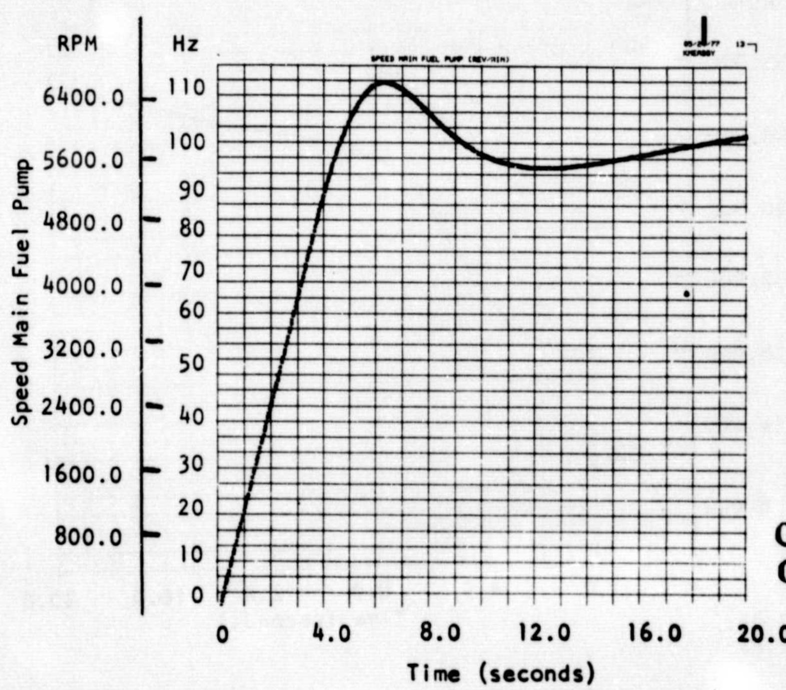

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Figure 33. Fuel Pump Speed vs Time (THI alt)

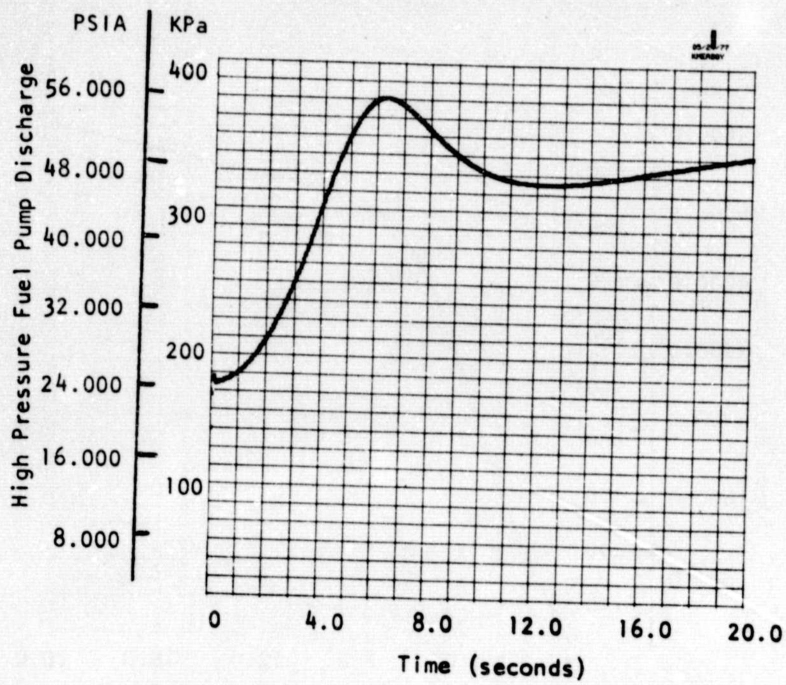

Figure 34. Fuel Pump High Pressure Discharge vs Time (THI alt)

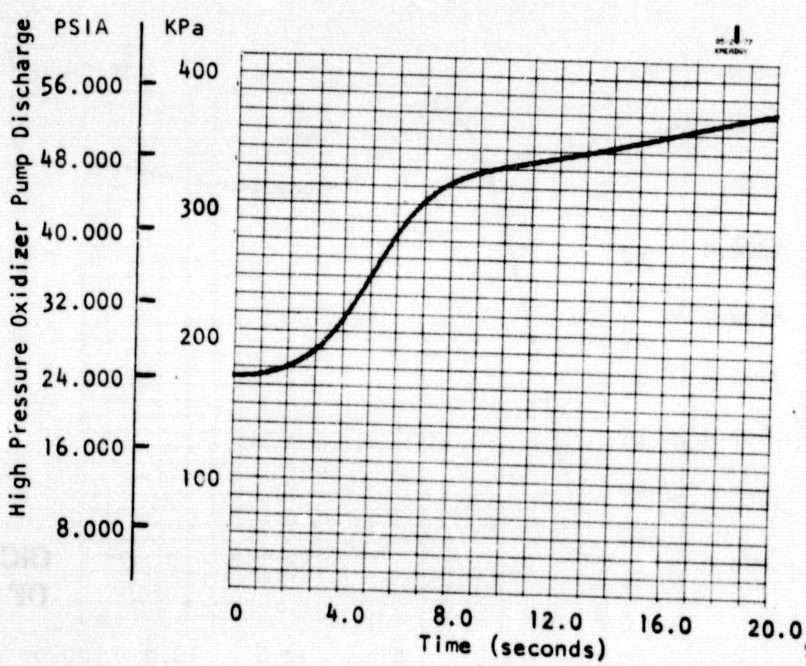

Figure 35. Oxidizer High Pressure Pump Discharge vs Time (THI alt)

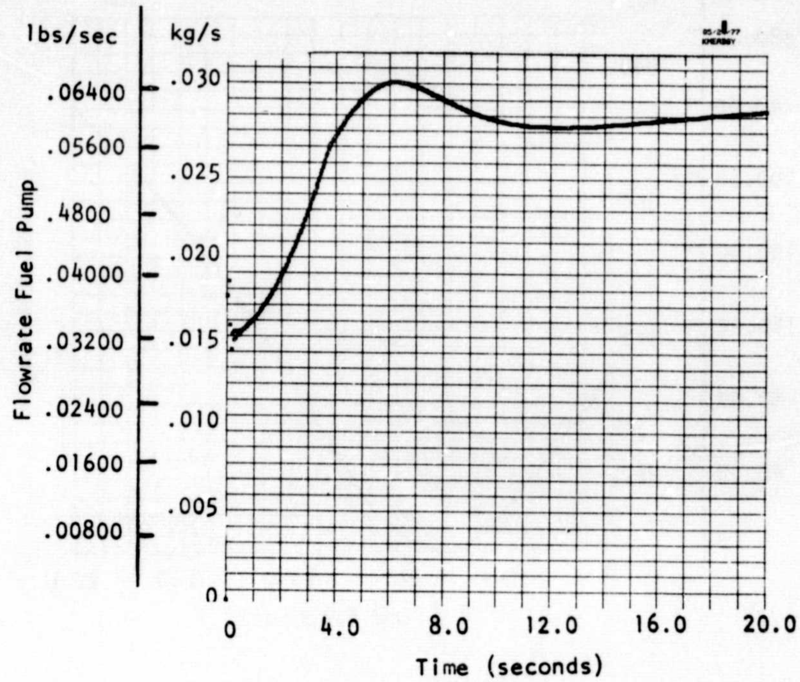

Figure 36. Fuel Pump Flowrate vs Time (THI alt)

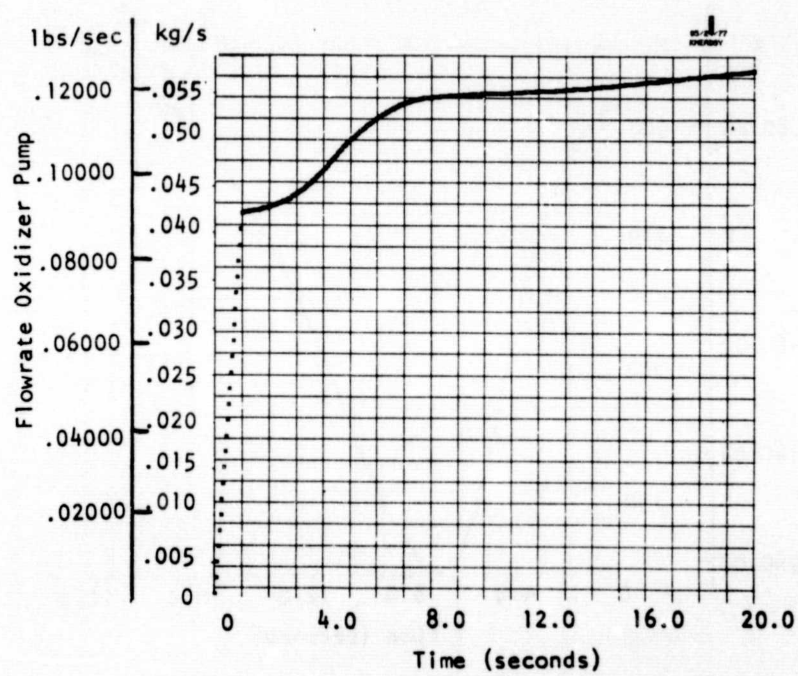

Figure 37. Oxidizer Pump Flowrate vs Time (THI alt)

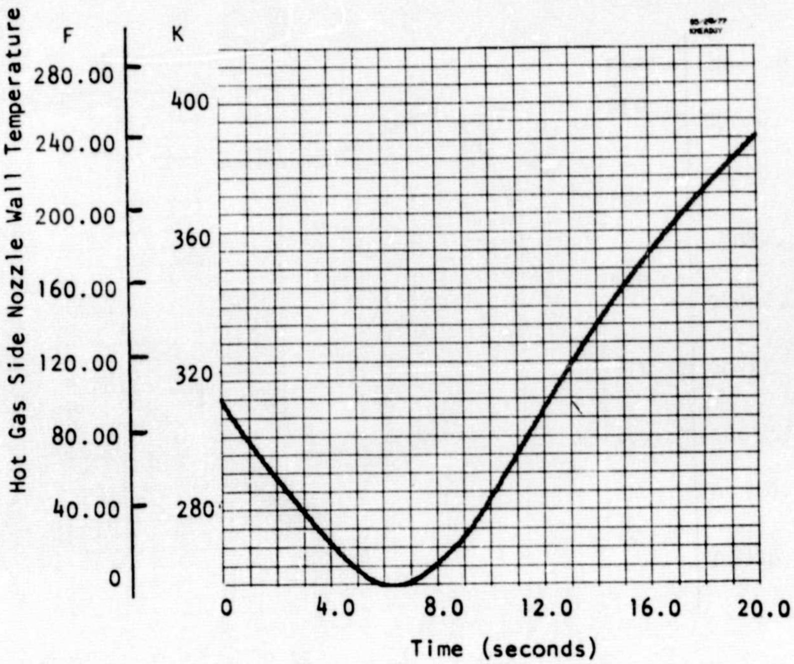

Figure 38. Hot Gas Nozzle Wall Temperature vs Time (THI alt)

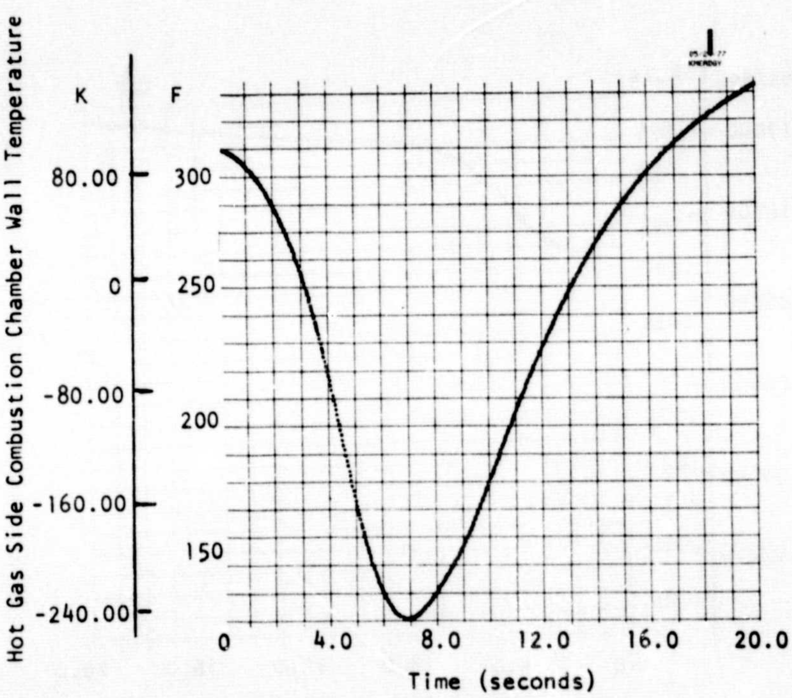

Figure 39. Hot Gas Combustion Chamber Wall Temperature vs Time (THI alt)

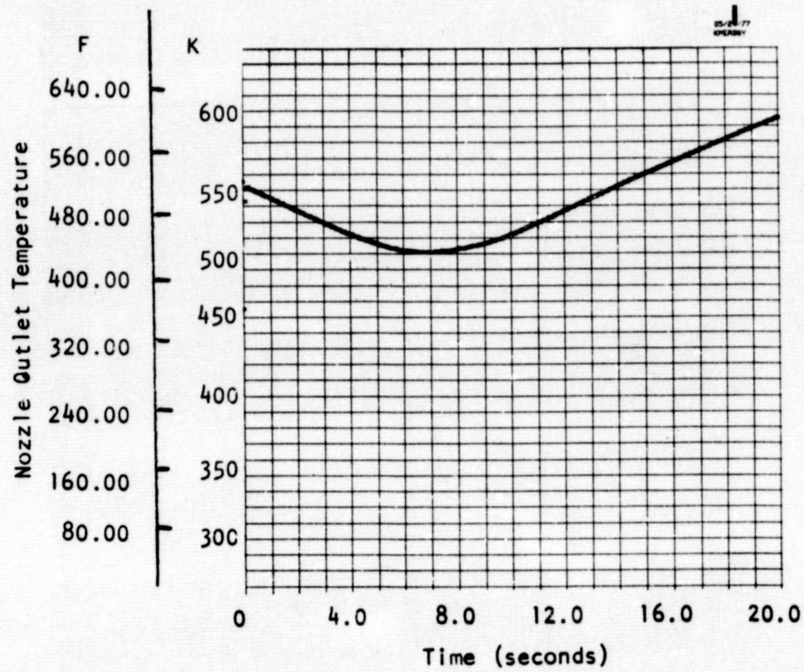

Figure 40. Nozzle Outlet Temperature vs Time (THI alt)

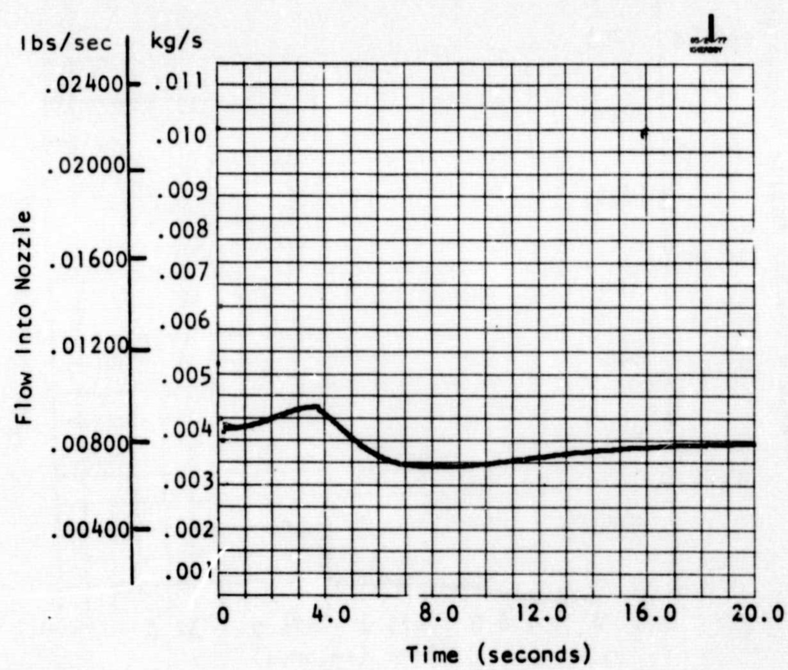

Figure 41. Nozzle Inlet Flow vs Time (THI alt)

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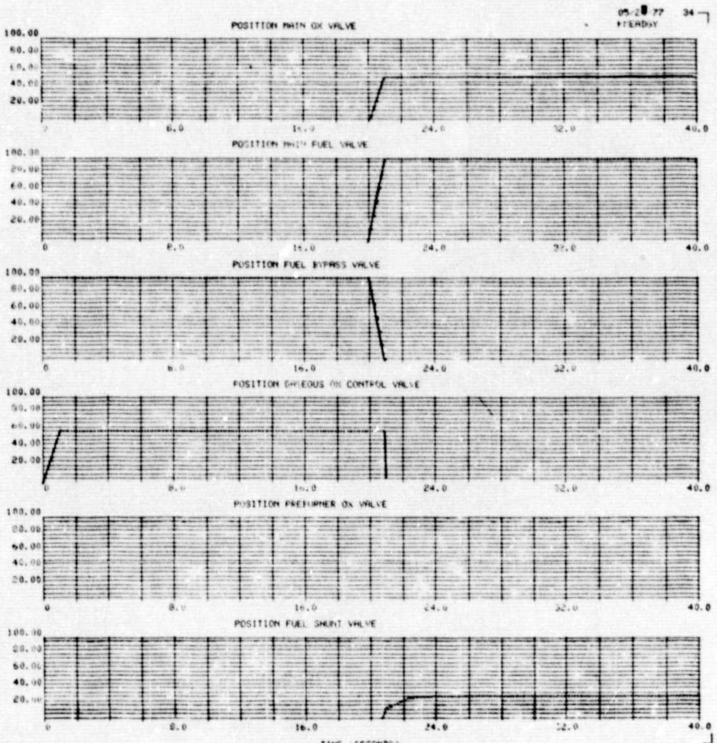

Figure 42. Valve Position vs Time (PI alt)

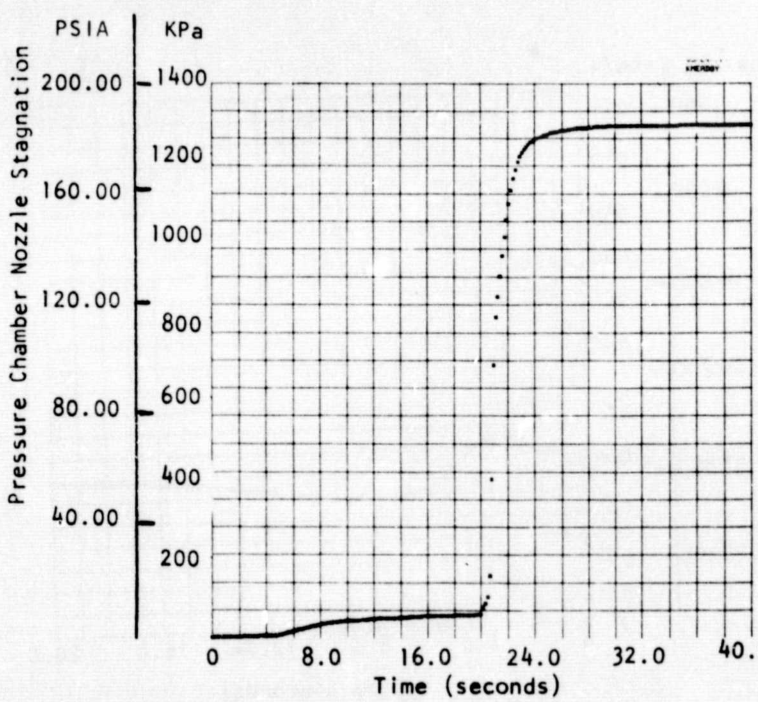

Figure 43. Chamber Pressure vs Time (PI alt)

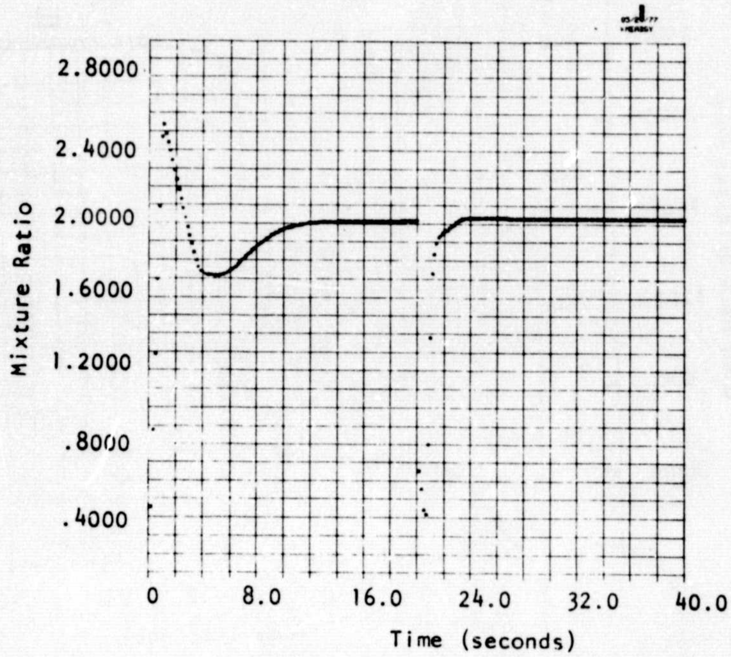

Figure 44. Mixture Ratio vs Time (PI alt)

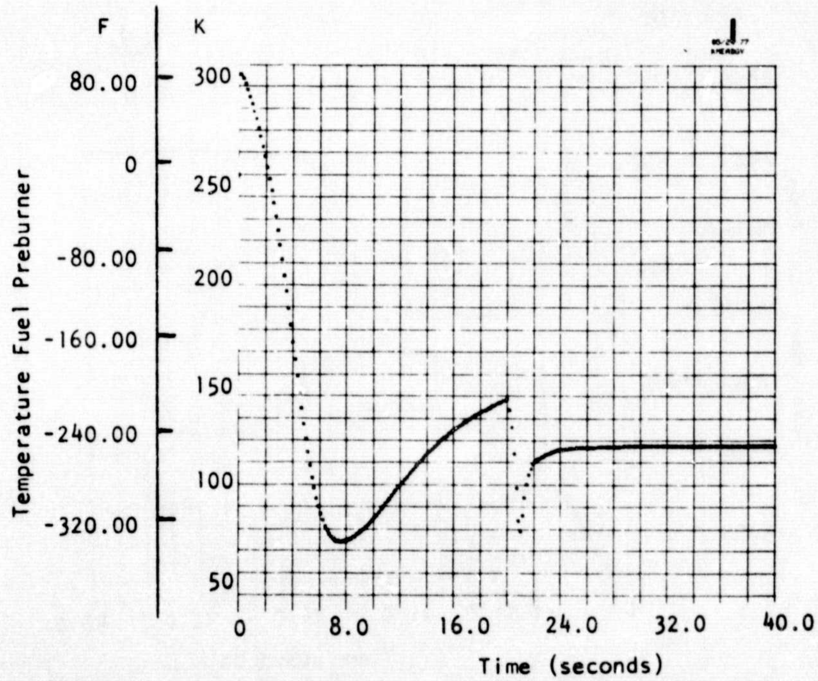

Figure 45. Temperature Fuel Preburner vs Time (PI alt)

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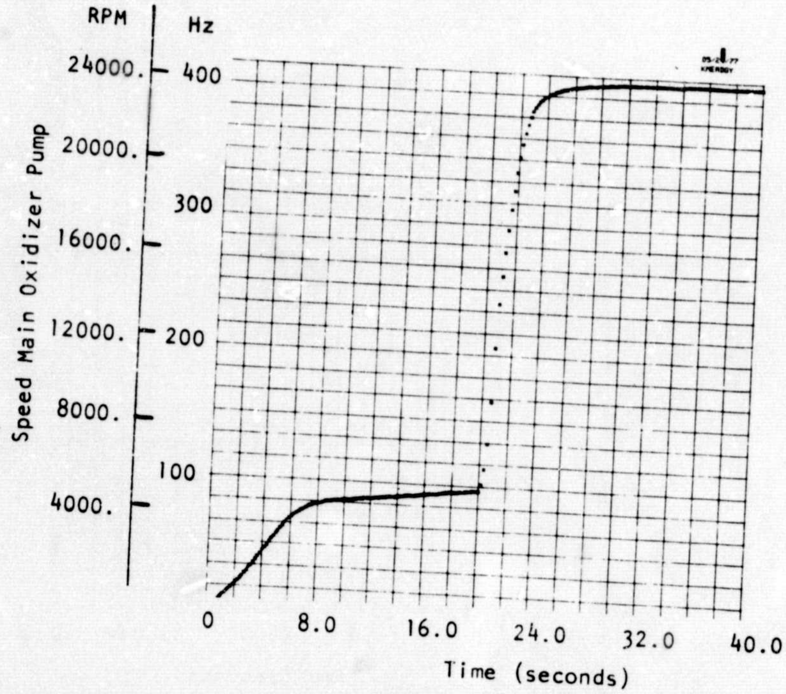

Figure 46. Oxidizer Pump Speed vs Time (PI alt)

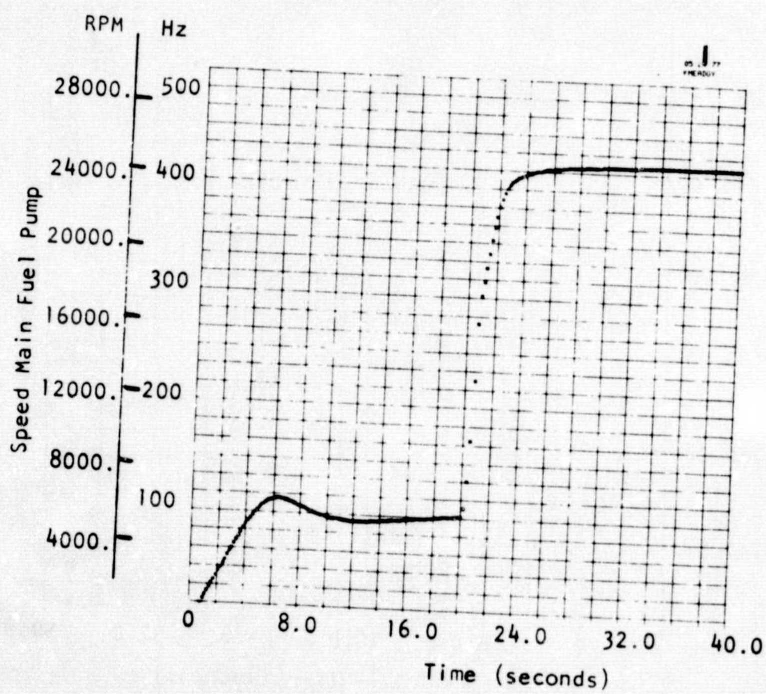

Figure 47. Fuel Pump Speed vs Time (PI alt)

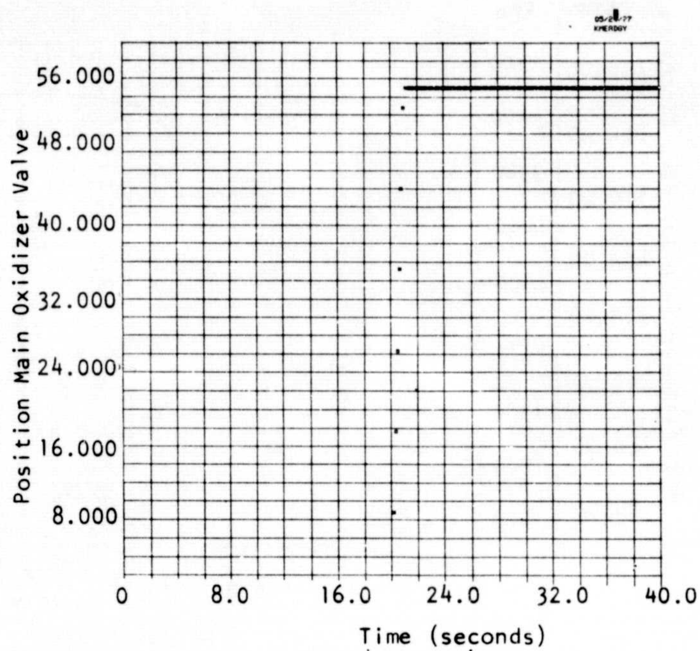

Figure 48. MOV Position vs Time (PI alt)

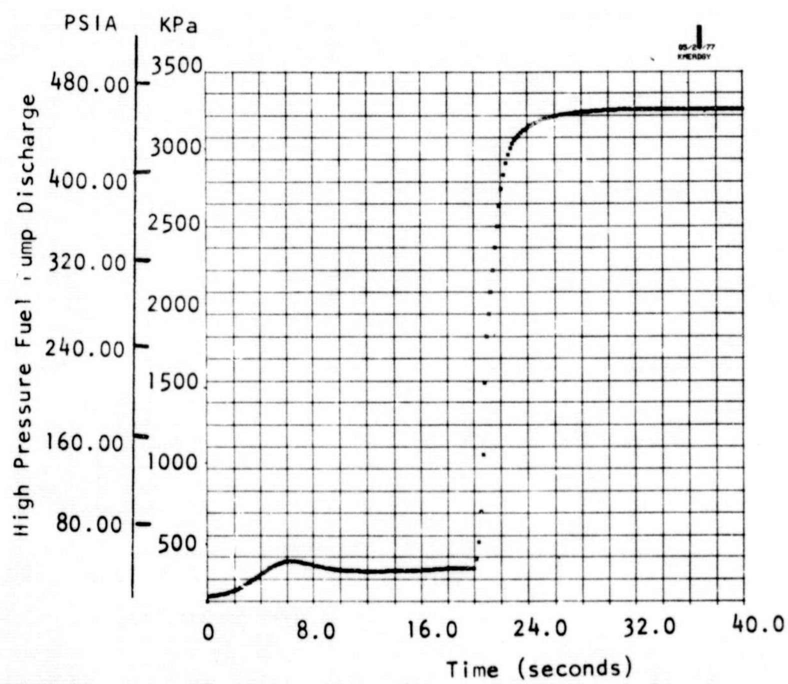

Figure 49. Fuel Pump Discharge Pressure vs Time (PI alt)

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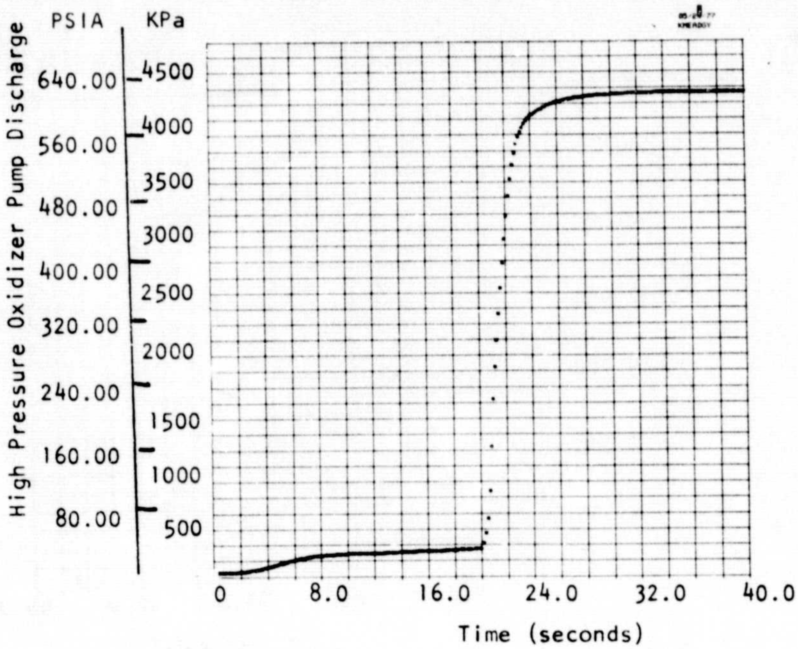

Figure 50. Oxidizer Pump Discharge Pressure vs Time (PI alt)

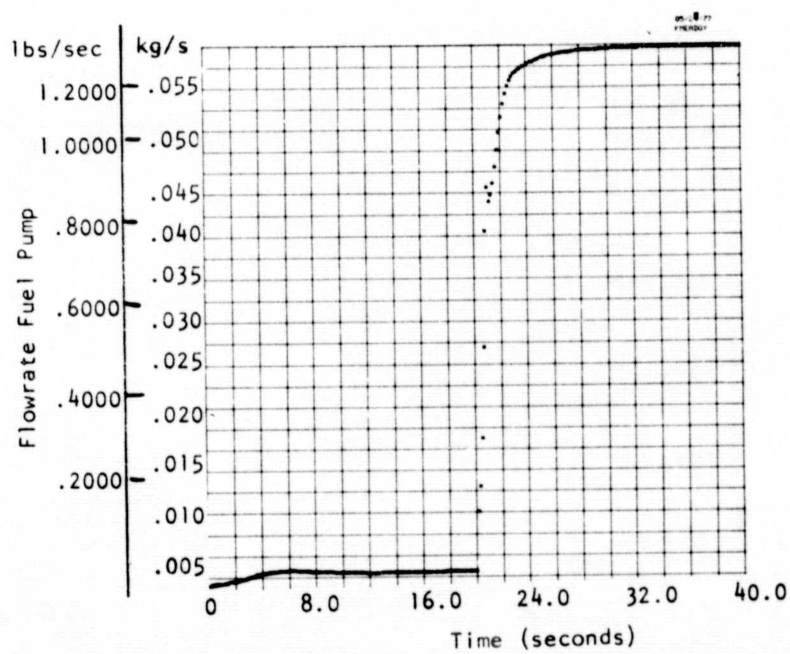

Figure 51. Fuel Pump Flowrate vs Time (PI alt)

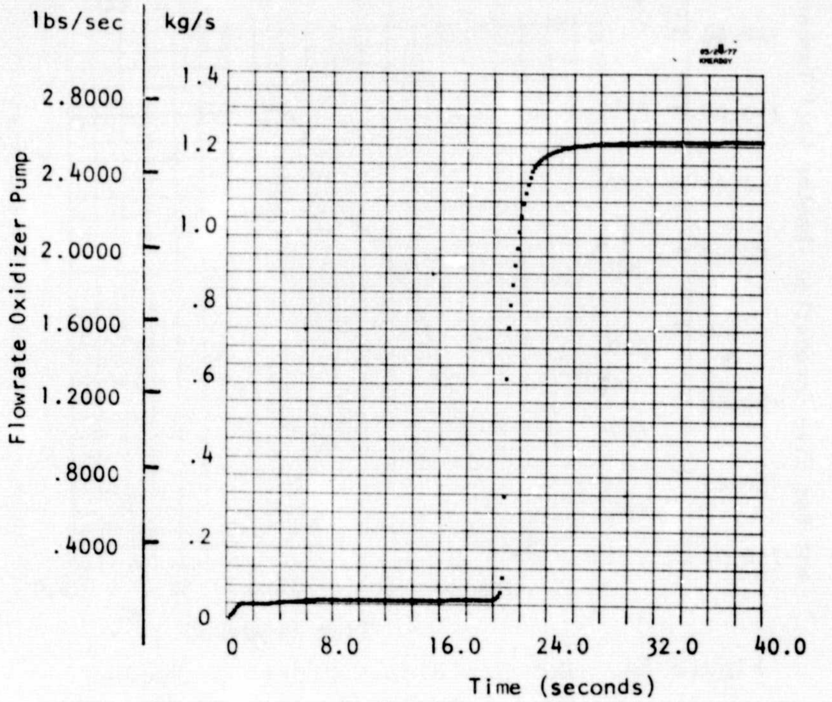

Figure 52. Oxidizer Pump Flowrate vs Time (PI alt)

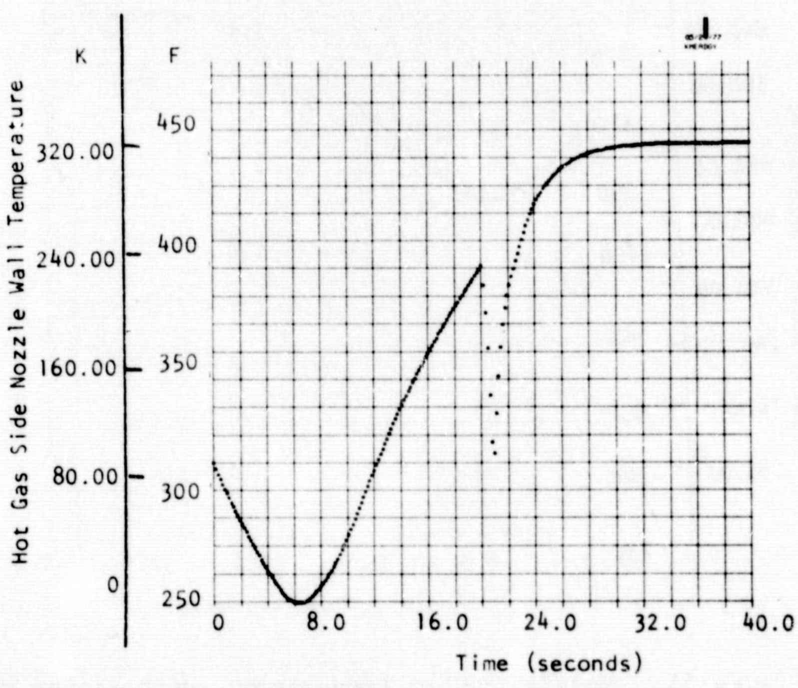

Figure 53. Hot Gas Nozzle Wall Temperature vs Time (PI alt)

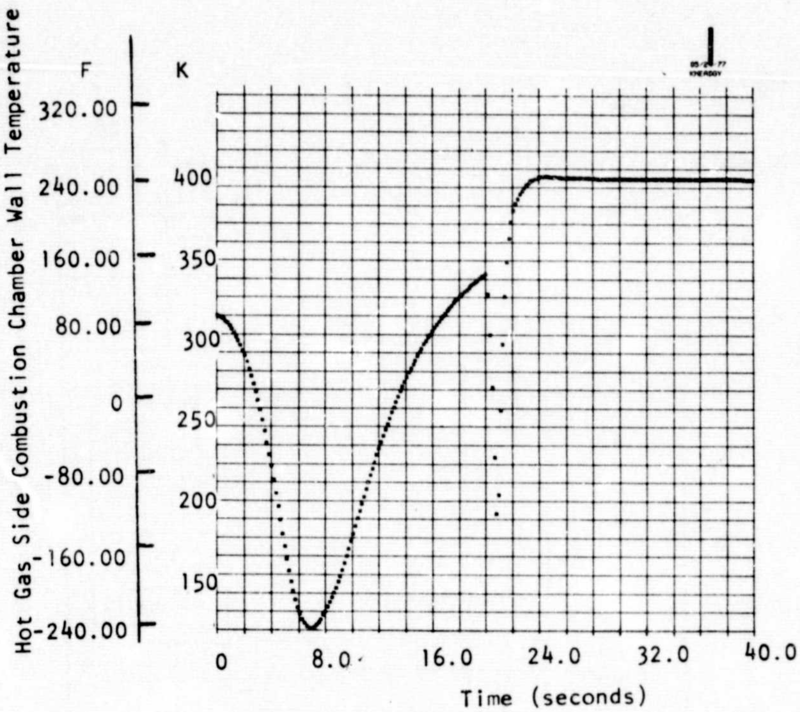

Figure 54. Hot Gas Side Combustion Chamber Wall Temperature vs Time (PI alt)

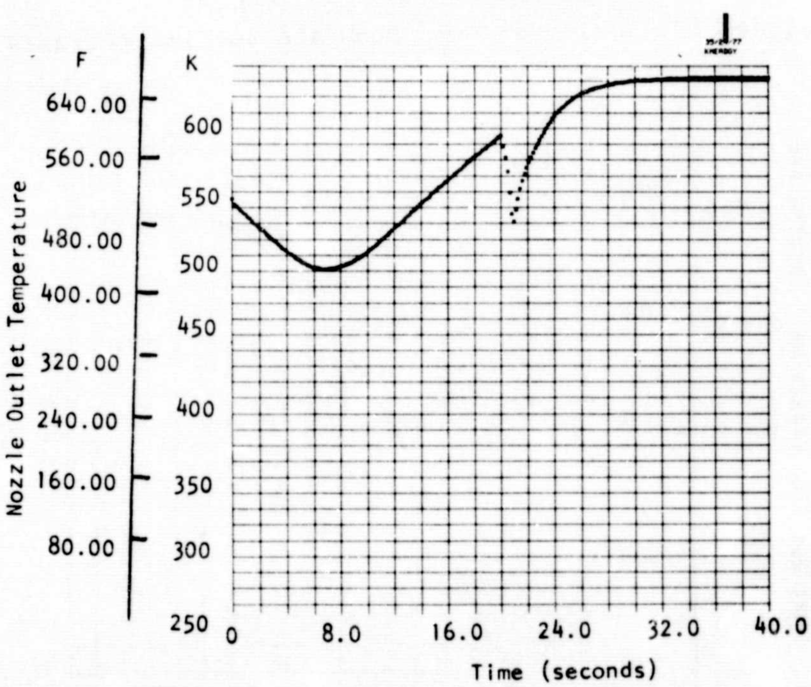

Figure 55. Nozzle Outlet Temperature vs Time (PI alt)

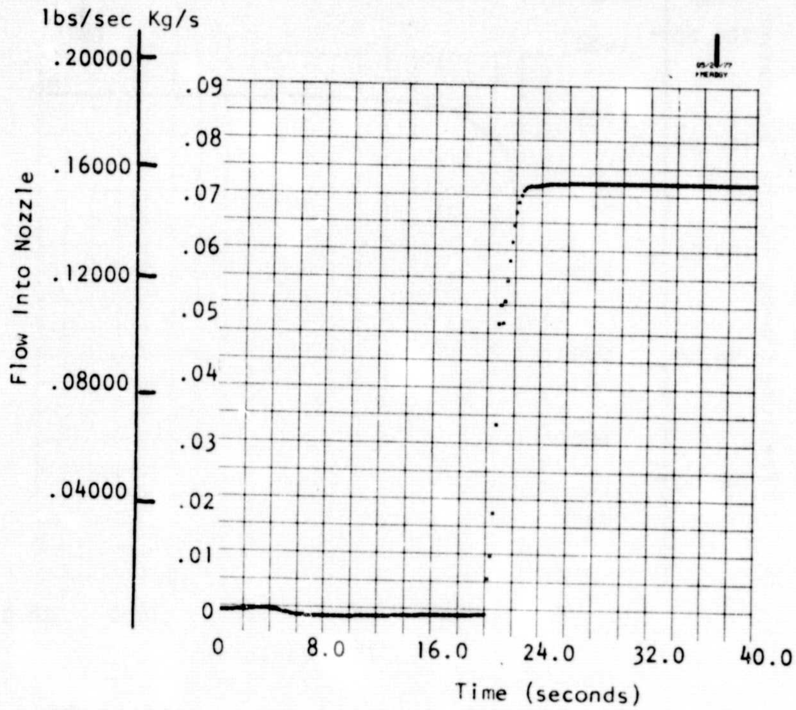

Figure 56. Flow Into Nozzle vs Time (PI alt)

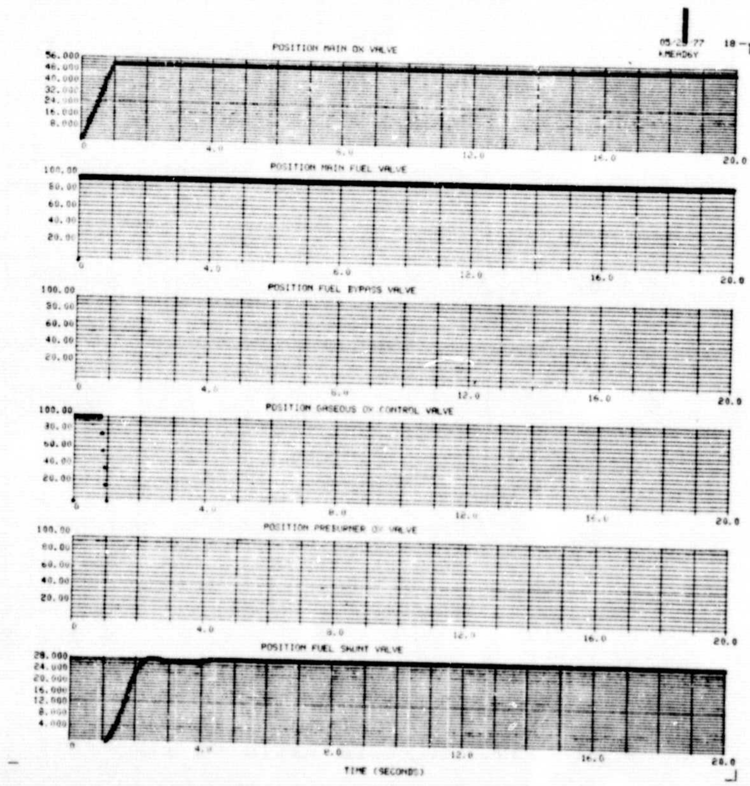

Figure 57. Valve Position vs Time (PI)

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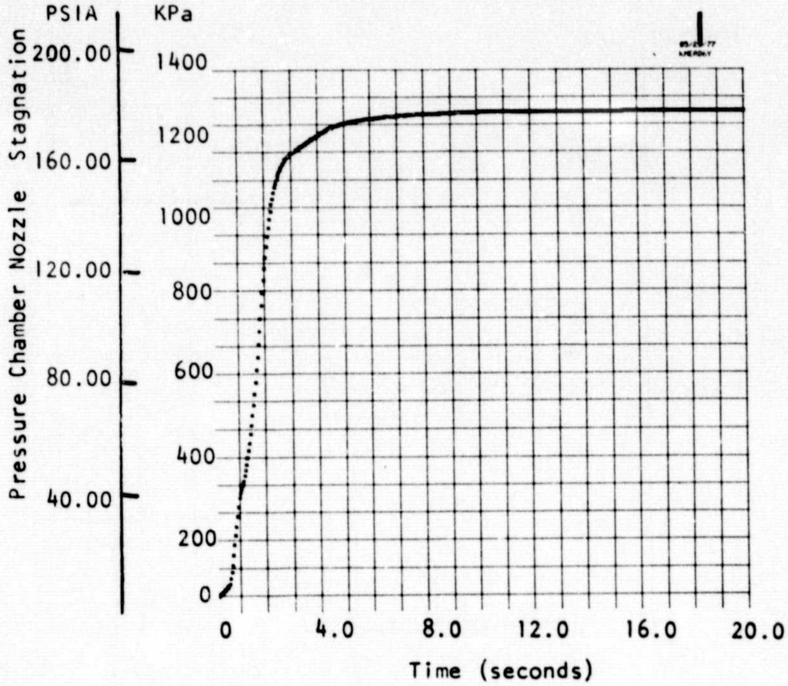

Figure 58. Chamber Pressure vs Time (PI)

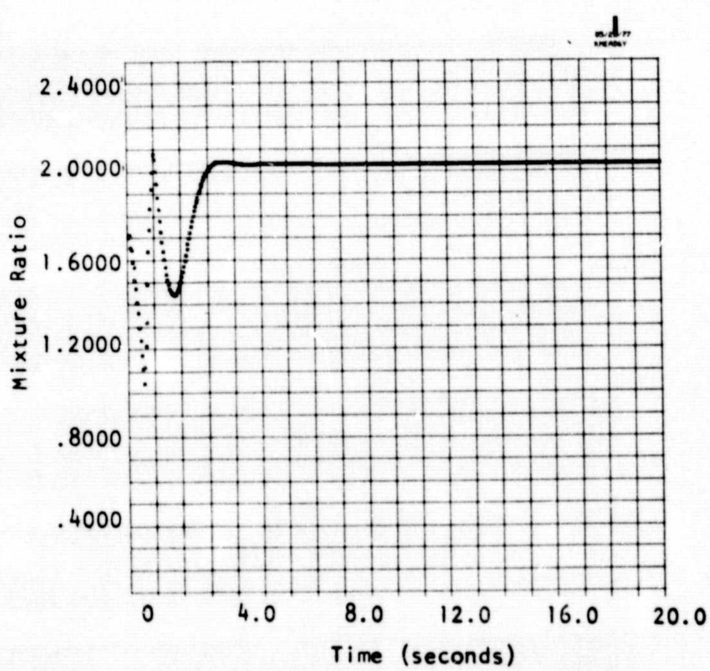

Figure 59. Mixture Ratio vs Time (PI)

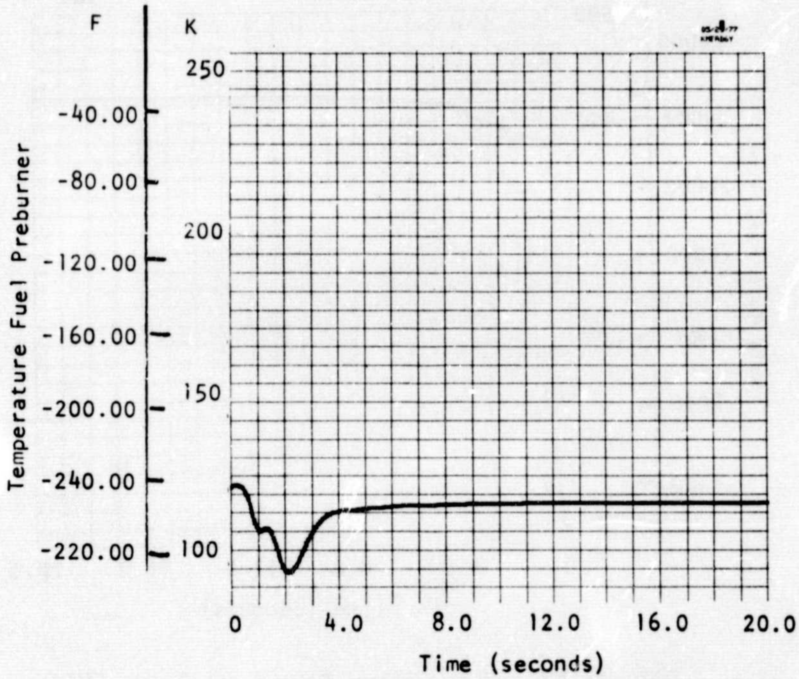

Figure 60. Preburner Temperature vs Time (PI)

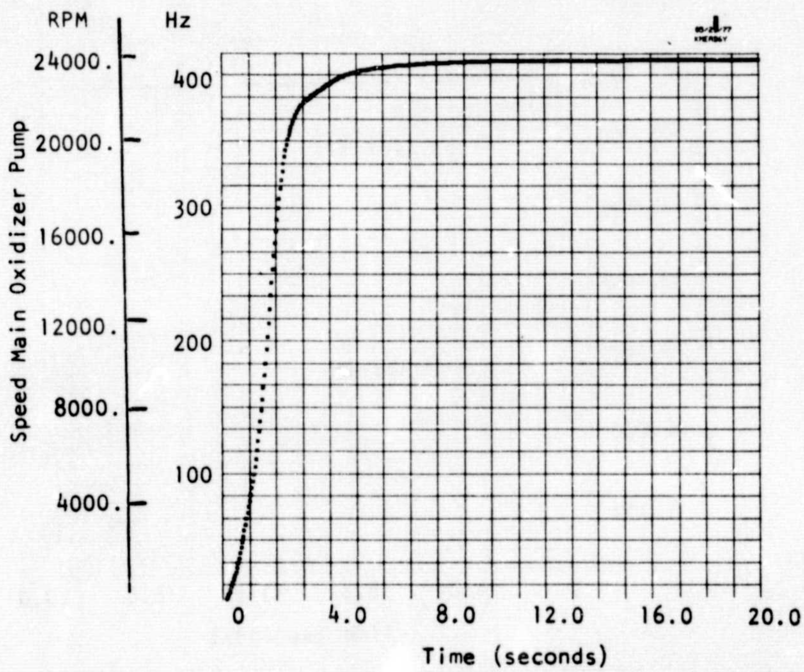

Figure 61. Oxidizer Pump Speed vs Time (PI)

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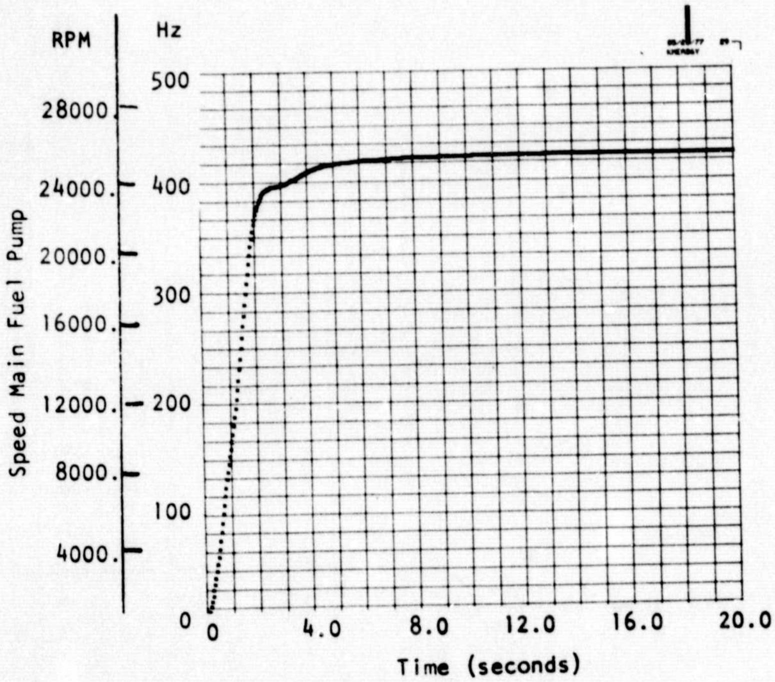

Figure 62. Fuel Pump Speed vs Time (PI)

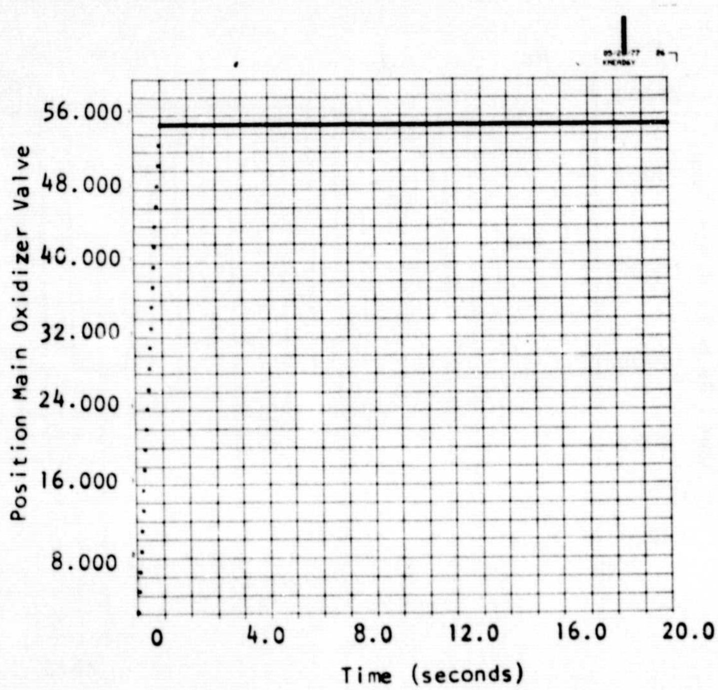

Figure 63. MOV Position vs Time (PI)

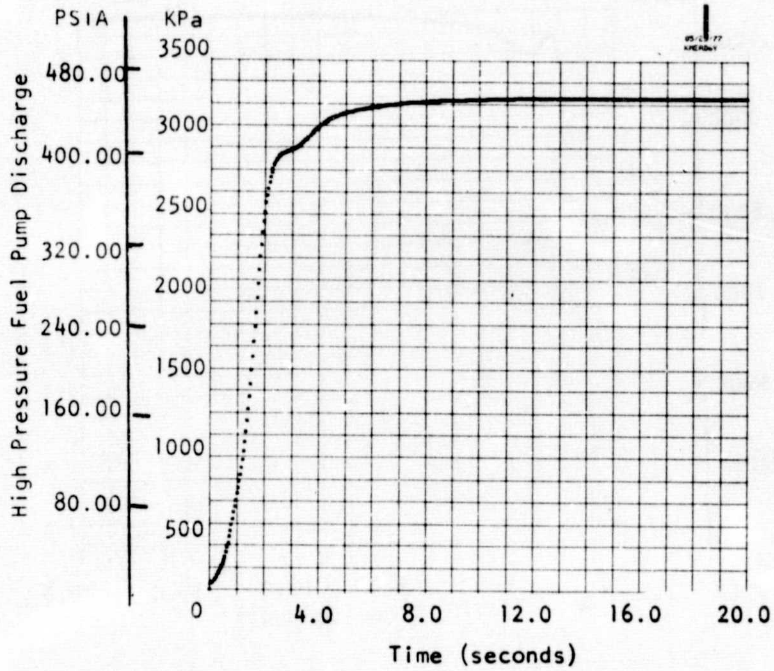

Figure 64. Fuel Pump Discharge Pressure vs Time (PI)

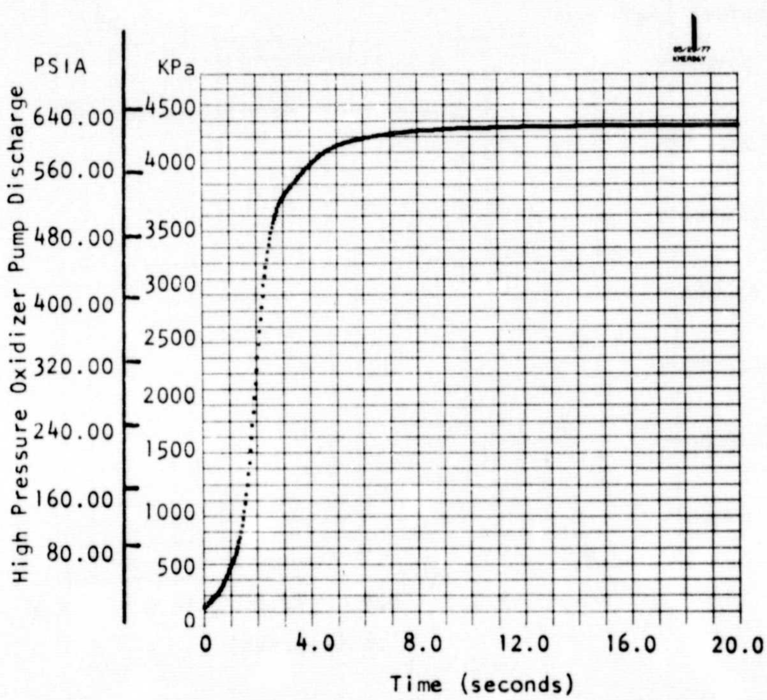

Figure 65. Oxidizer Pump Discharge Pressure vs Time (PI)

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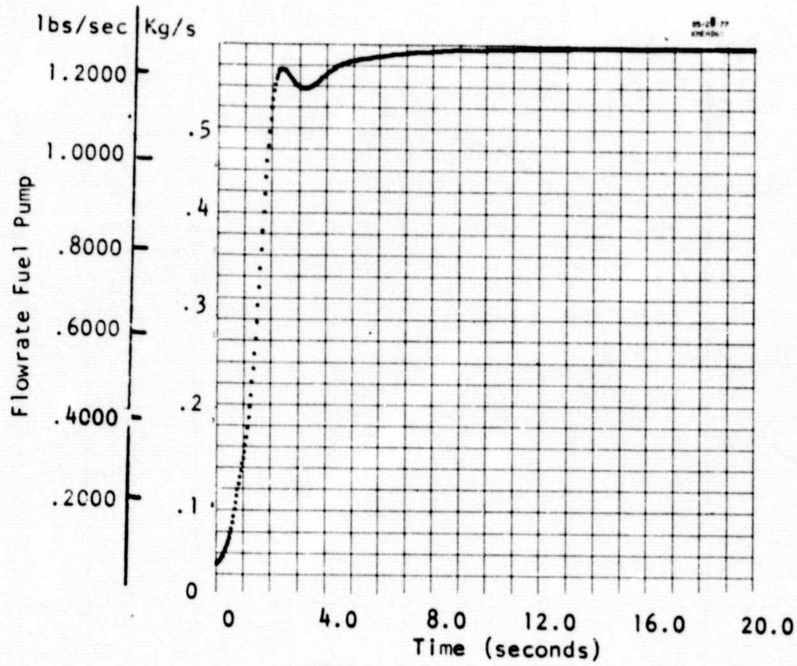

Figure 66. Fuel Pump Flowrate vs Time (PI)

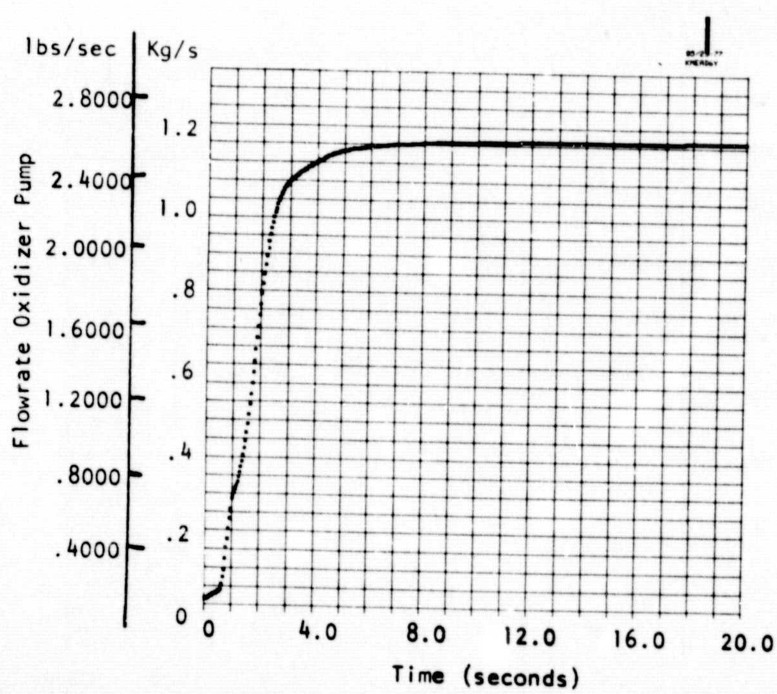

Figure 67. Oxidizer Pump Flowrate vs Time (PI)

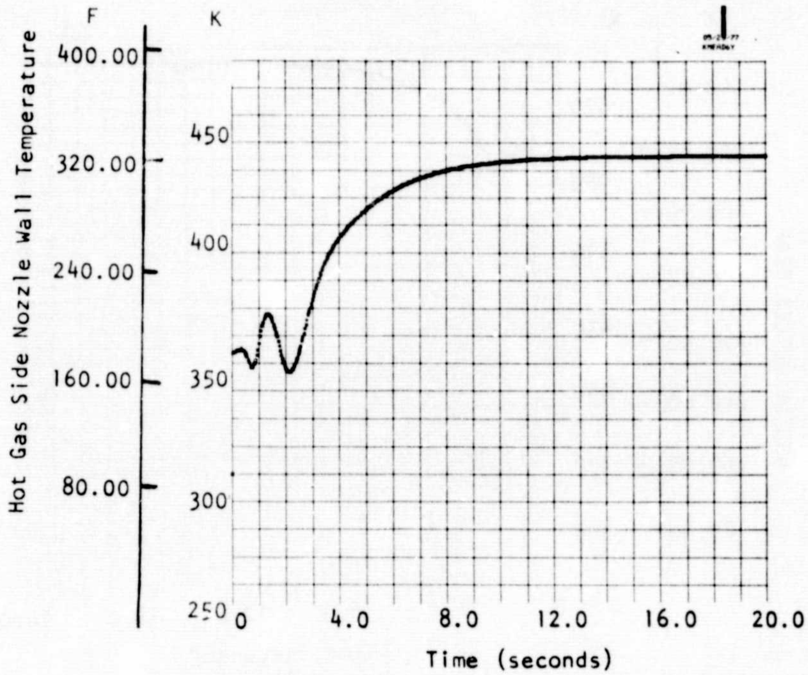

Figure 68. Hot Gas Side Nozzle Wall Temperature vs Time (PI)

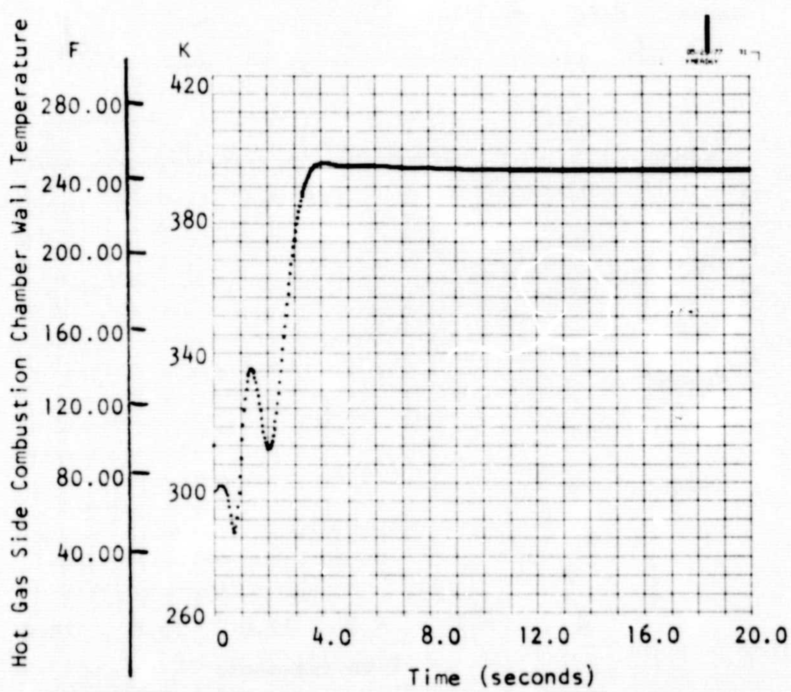

Figure 69. Hot Gas Side Combustion Chamber Wall Temperature vs Time (PI)

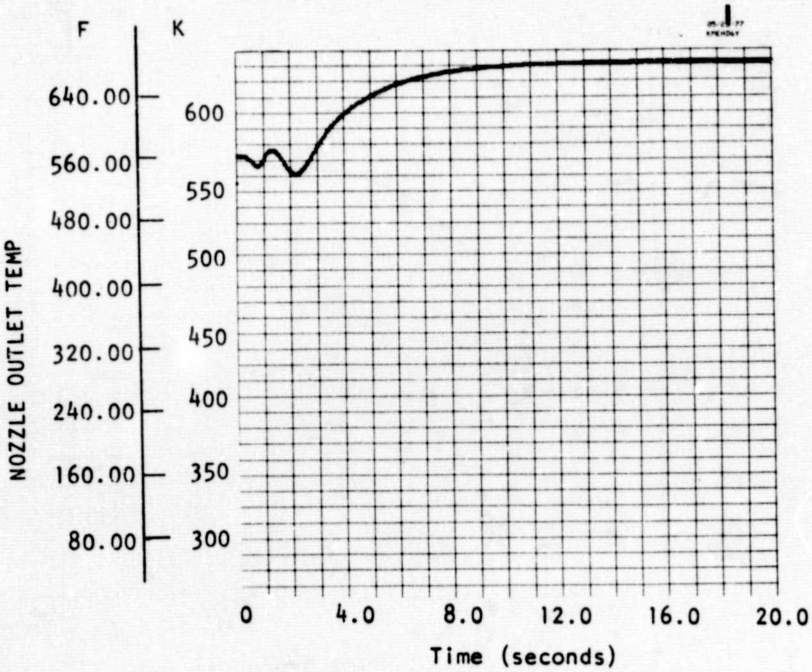

Figure 70. Nozzle Outlet Temperature vs Time (PI)

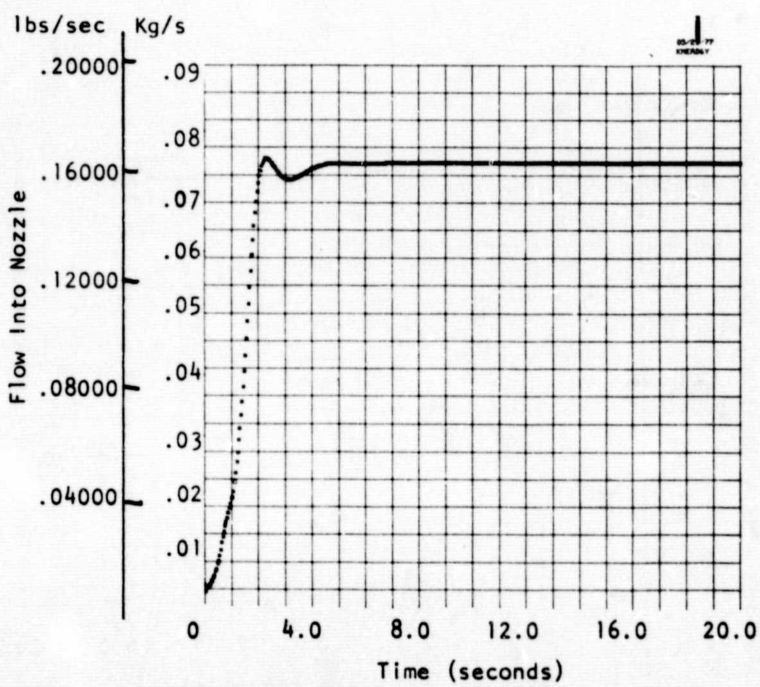

Figure 71. Flow Into Nozzle vs Time (PI)

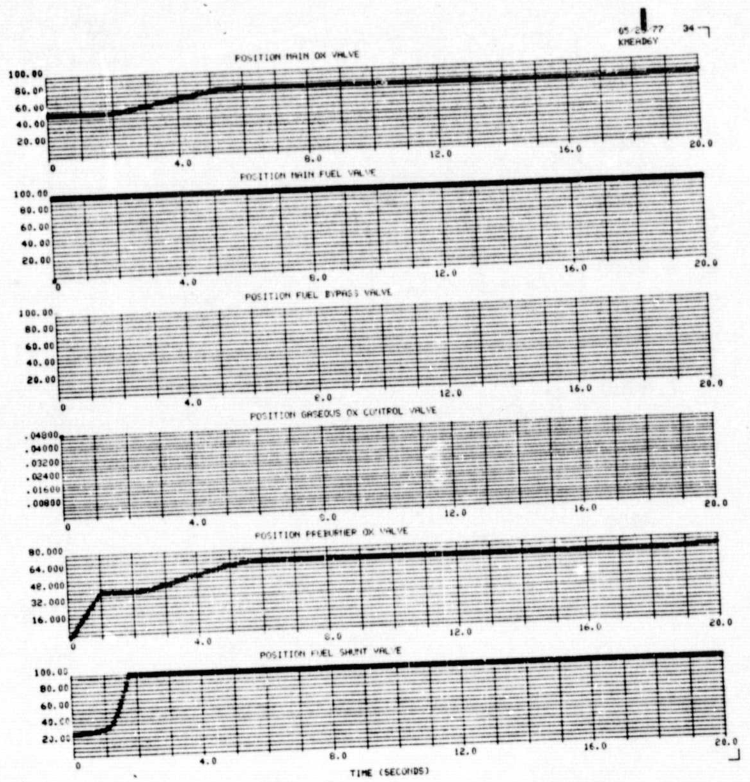

Figure 72. Valve Position vs Time (Mainstage)

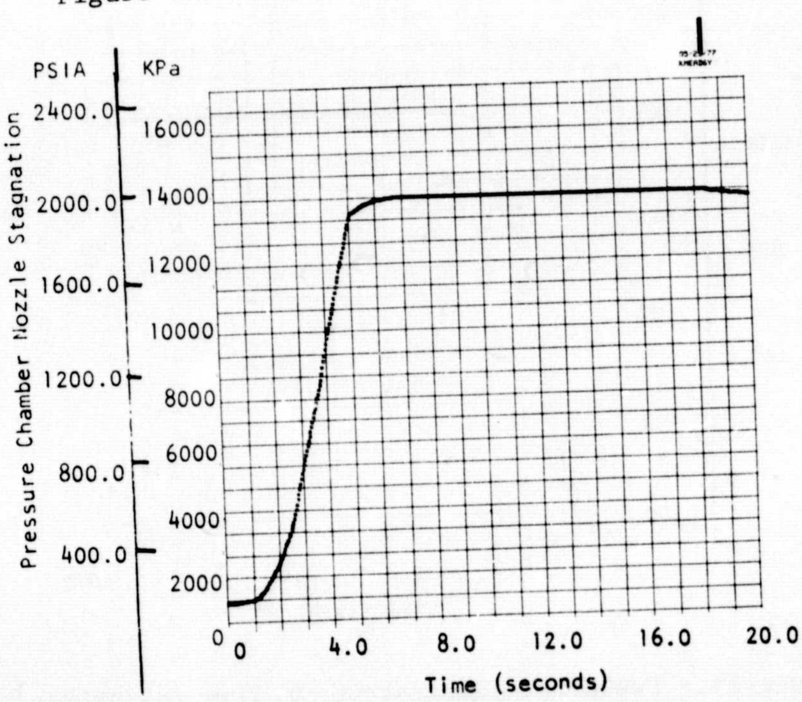

Figure 73. Chamber Pressure vs Time (Mainstage)

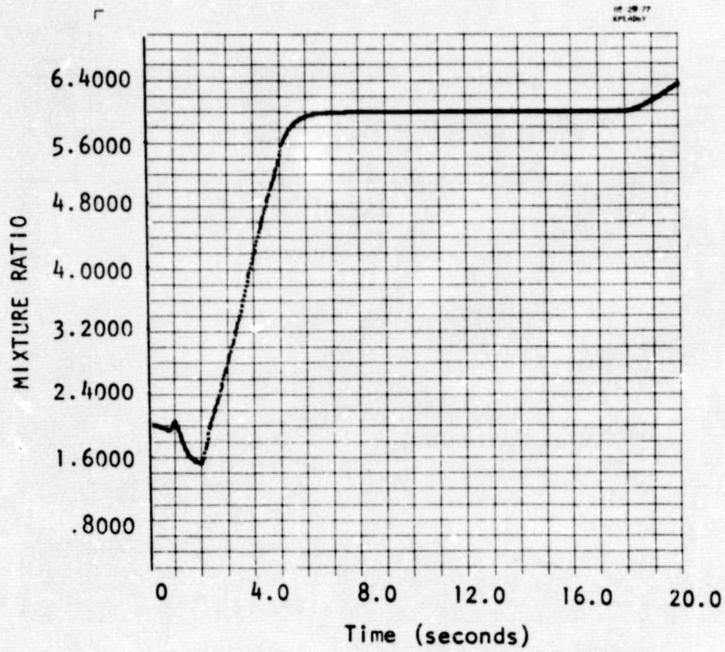

Figure 74. Mixture Ratio vs Time (Mainstage)

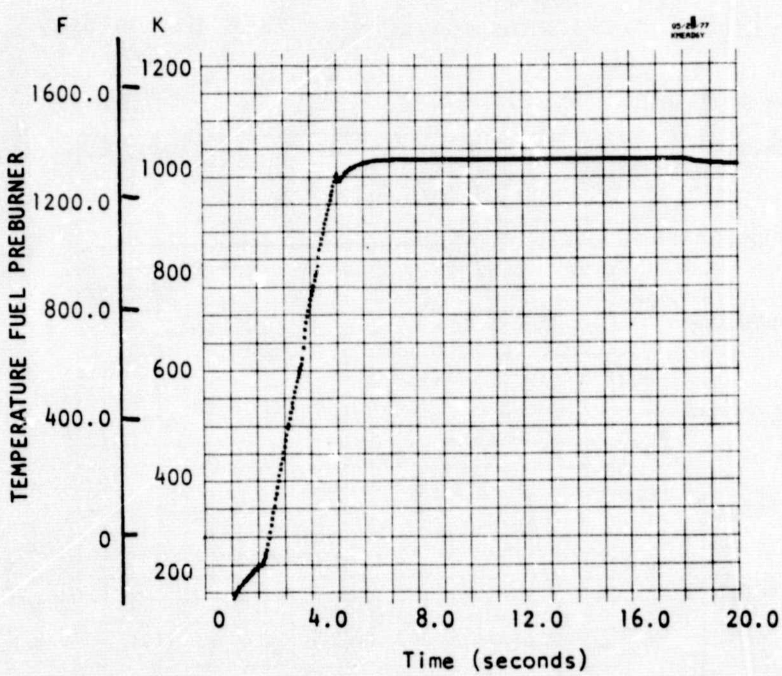

Figure 75. Preburner Temperature vs Time (Mainstage)

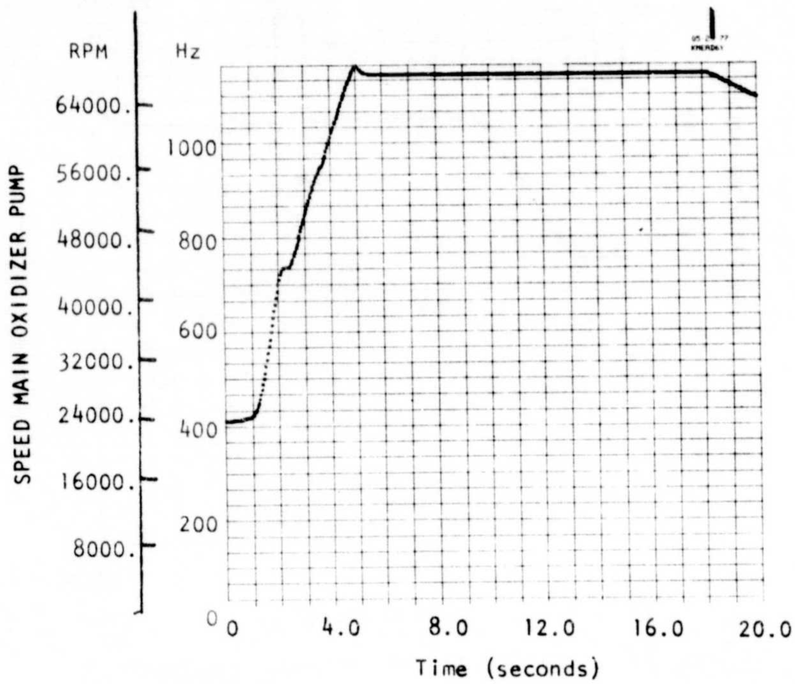

Figure 76. Oxidizer Pump Speed vs Time (Mainstage)

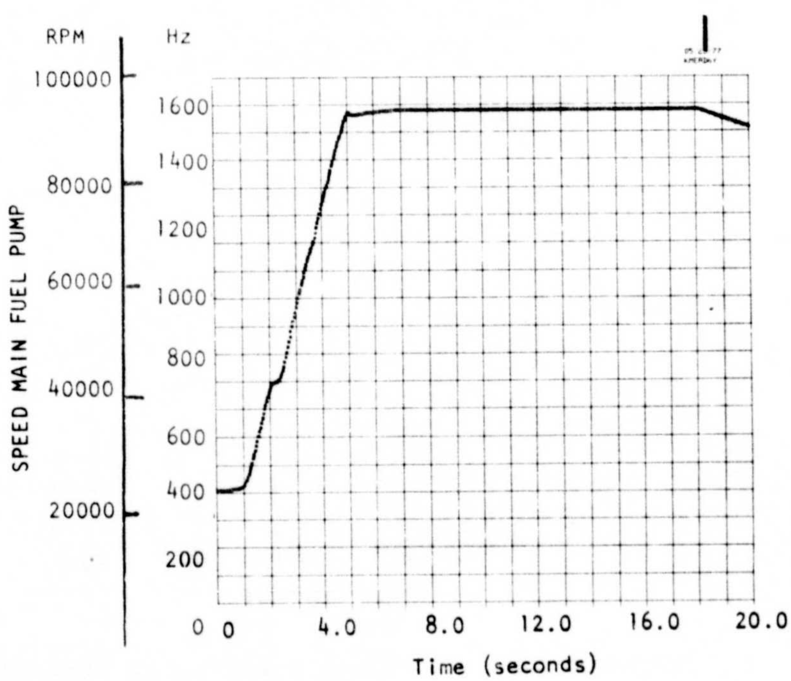

Figure 77. Fuel Pump Speed vs Time (Mainstage)

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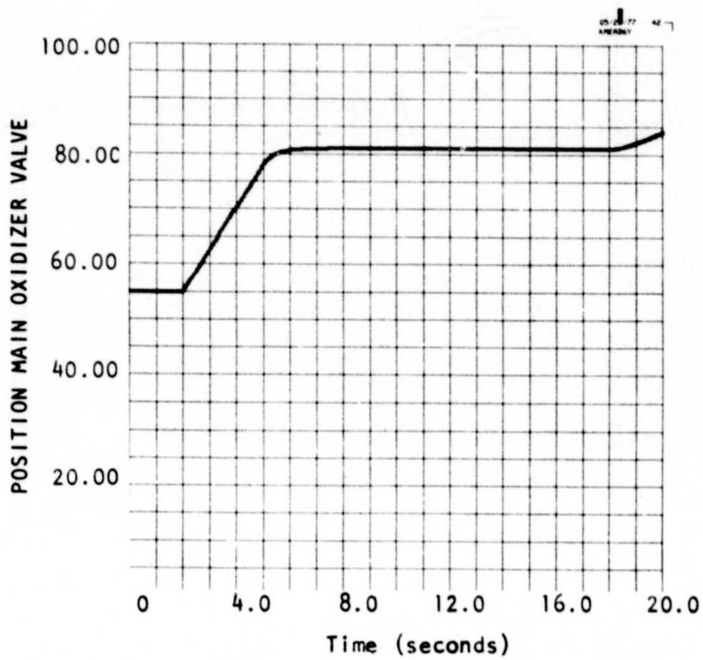

Figure 78. MOV Position vs Time (Mainstage)

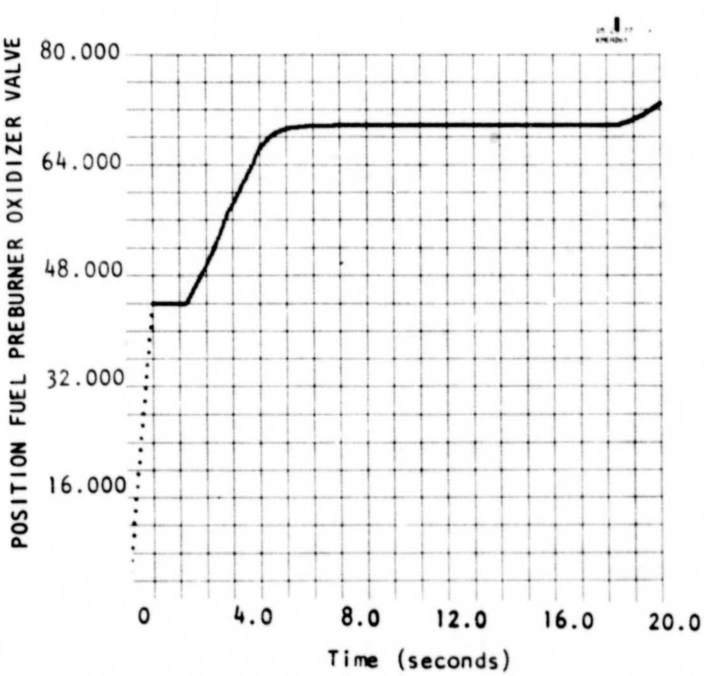

Figure 79. Preburner Oxidizer Valve Position vs Time (Mainstage)

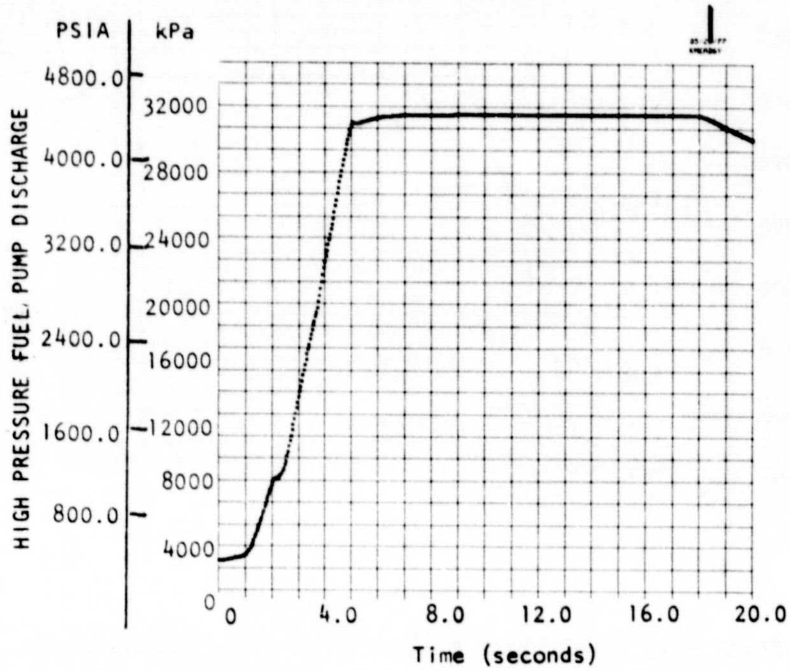

Figure 80. Fuel Pump Discharge Pressure vs Time (Mainstage)

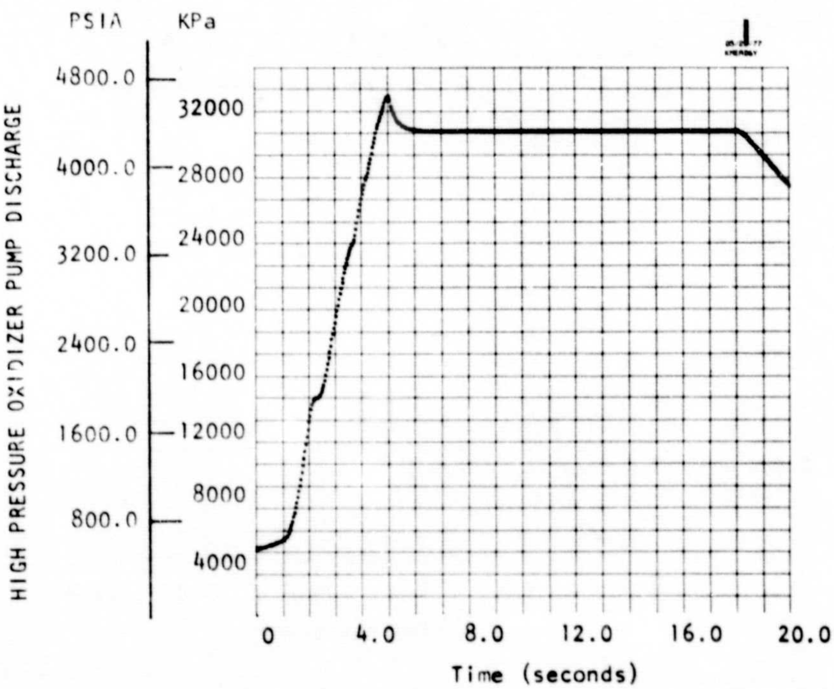

Figure 81. Oxidizer Pump Discharge Pressure vs Time (Mainstage)

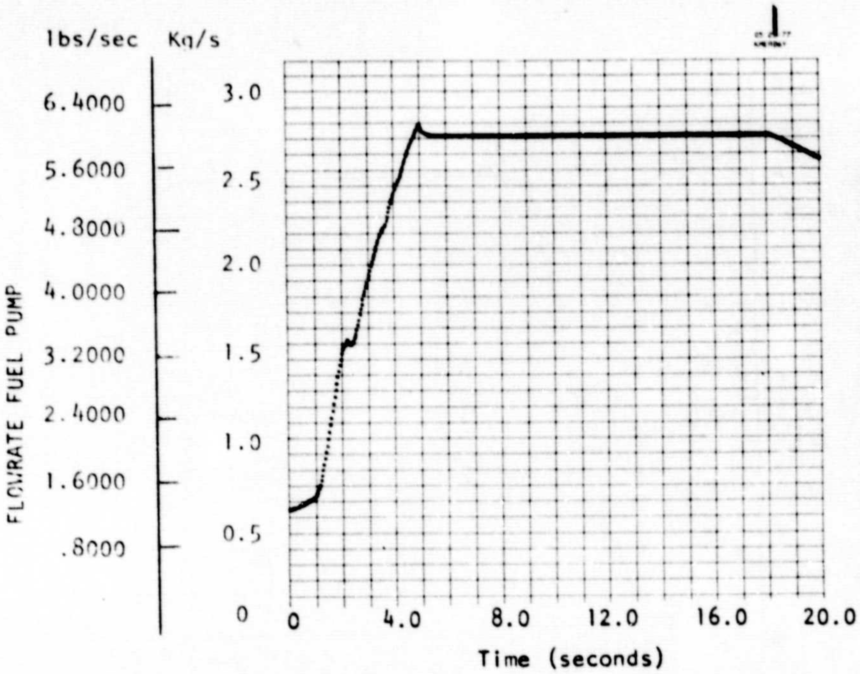

Figure 82. Fuel Pump Flowrate vs Time (Mainstage)

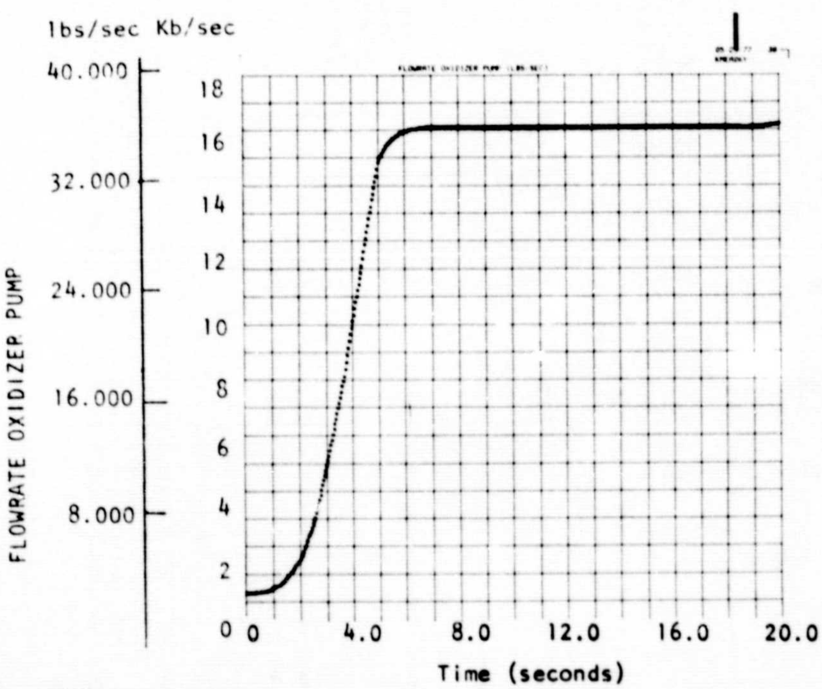

Figure 83. Oxidizer Pump Flowrate vs Time (Mainstage)

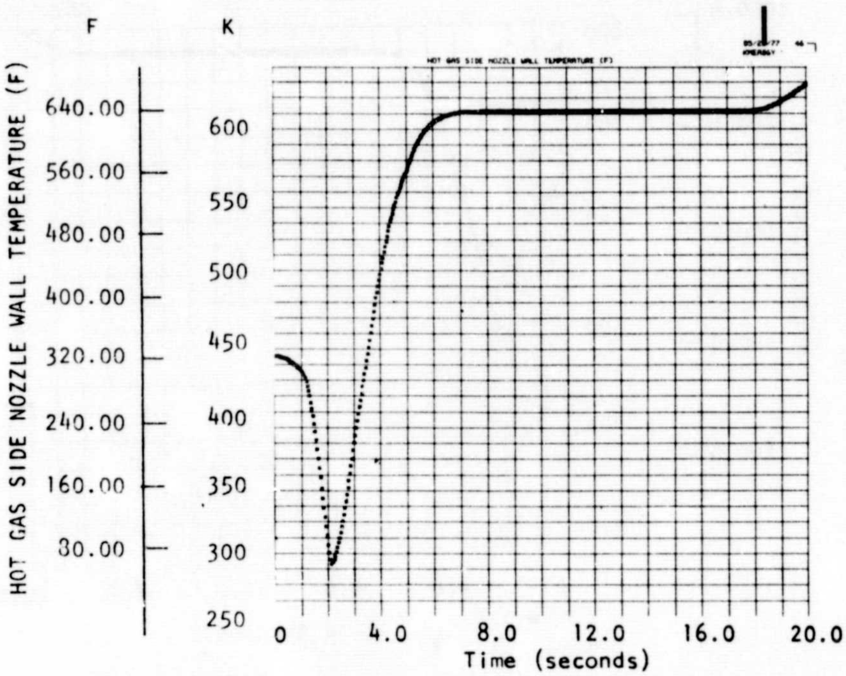

Figure 84. Hot Gas Side Nozzle Wall Temperature vs Time (Mainstage)

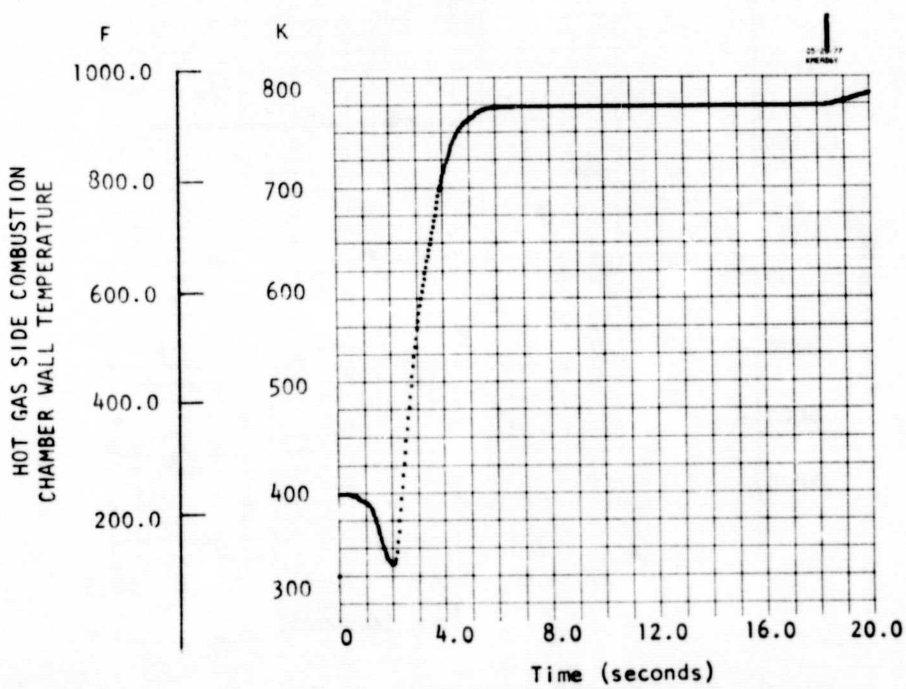

Figure 85. Hot Gas Side Combustion Chamber Wall Temperature vs Time (Mainstage)

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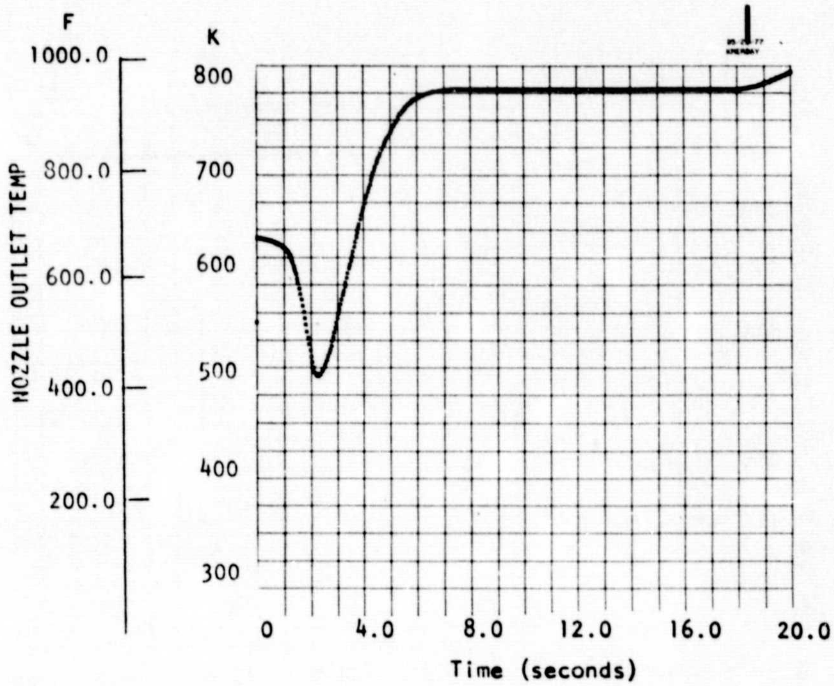

Figure 86. Nozzle Outlet Temperature vs Time (Mainstage)

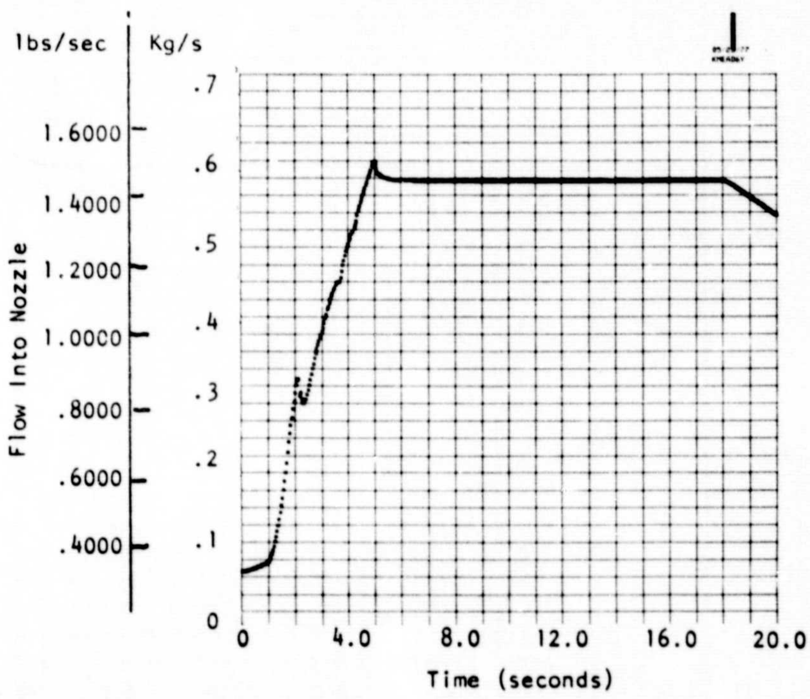

Figure 87. Flow Into Nozzle vs Time (Mainstage)

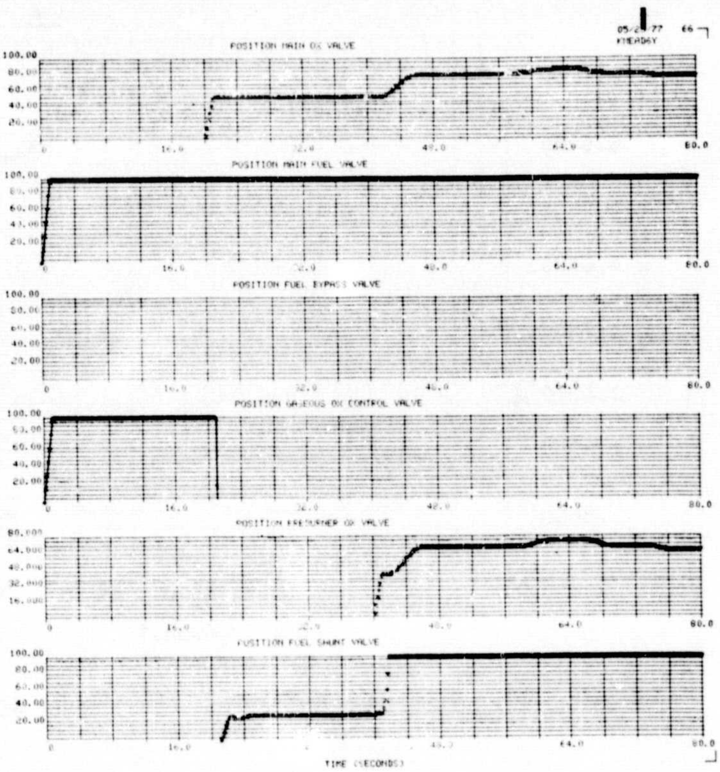

Figure 88. Valve Position vs Time (Summary)

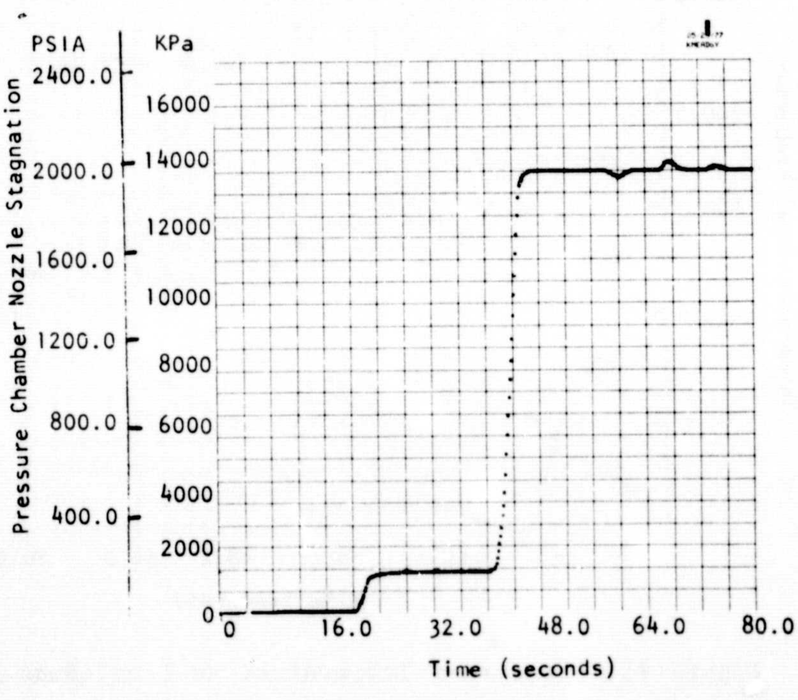

Figure 89. Chamber Pressure vs Time (Summary)

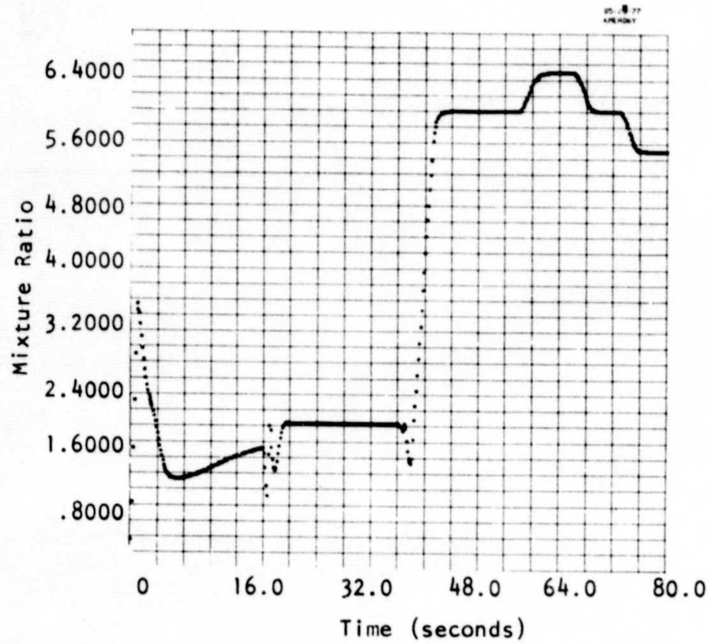

Figure 90. Mixture Ratio vs Time (Summary)

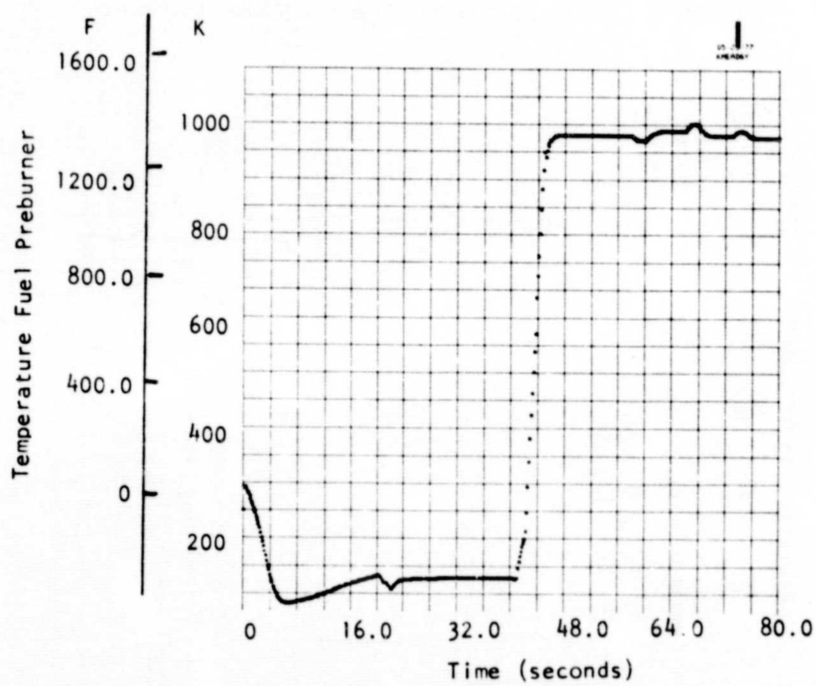

Figure 91. Preburner Temperature vs Time (Summary)

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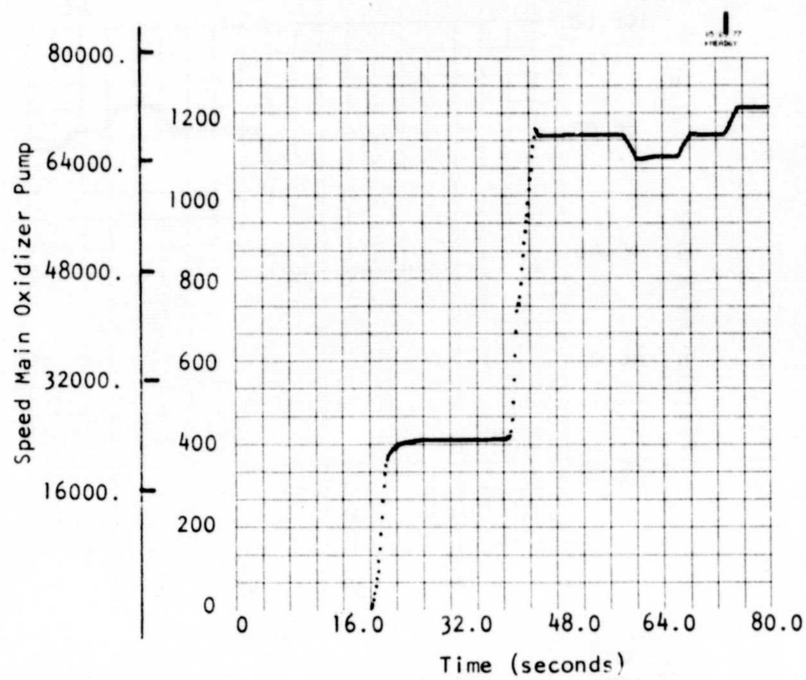

Figure 92. Oxidizer Pump Speed vs Time (Summary)

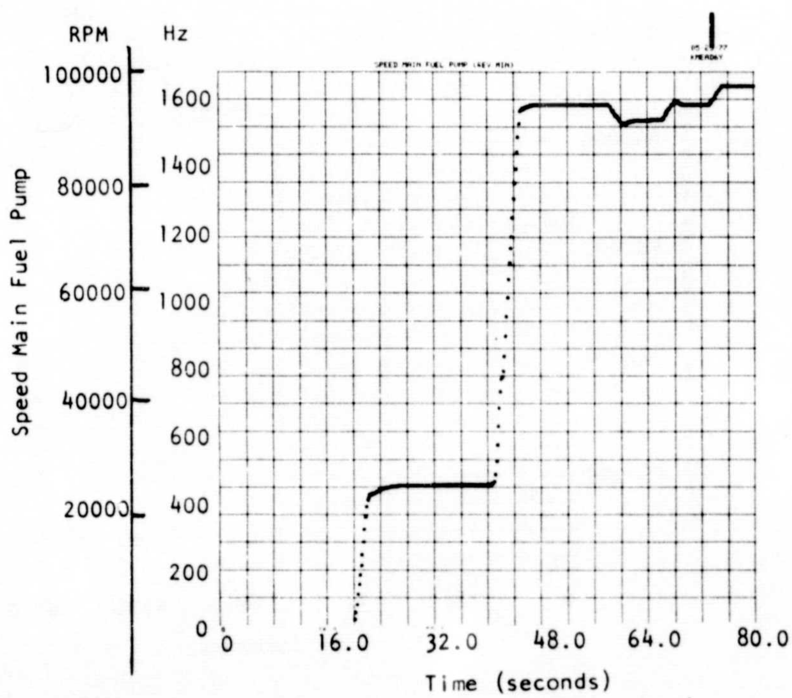

Figure 93. Fuel Pump Speed vs Time (Summary)

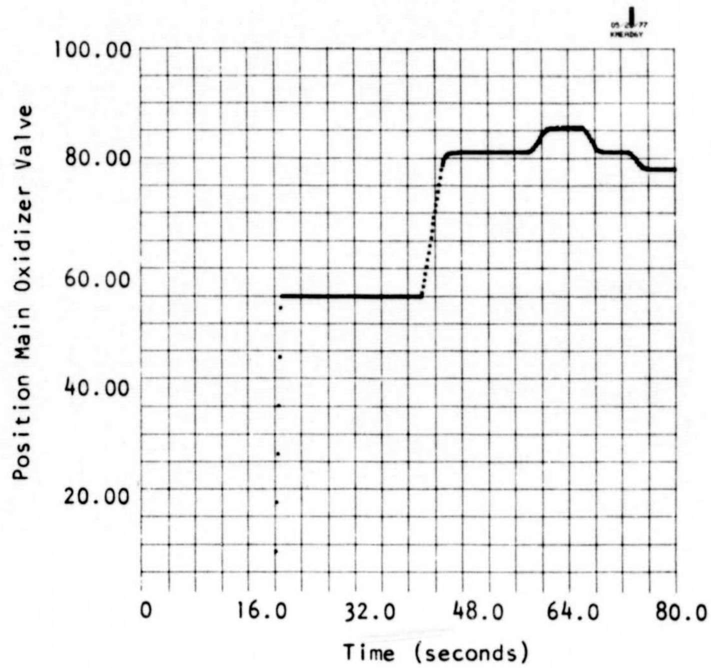

Figure 94. MOV Position vs Time (Summary)

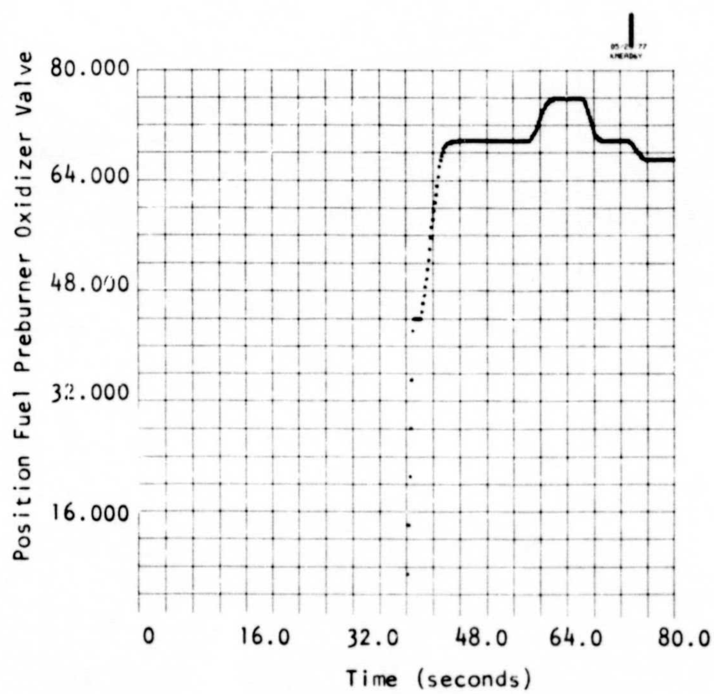

Figure 95. Preburner Oxidizer Valve Position vs Time (Summary)

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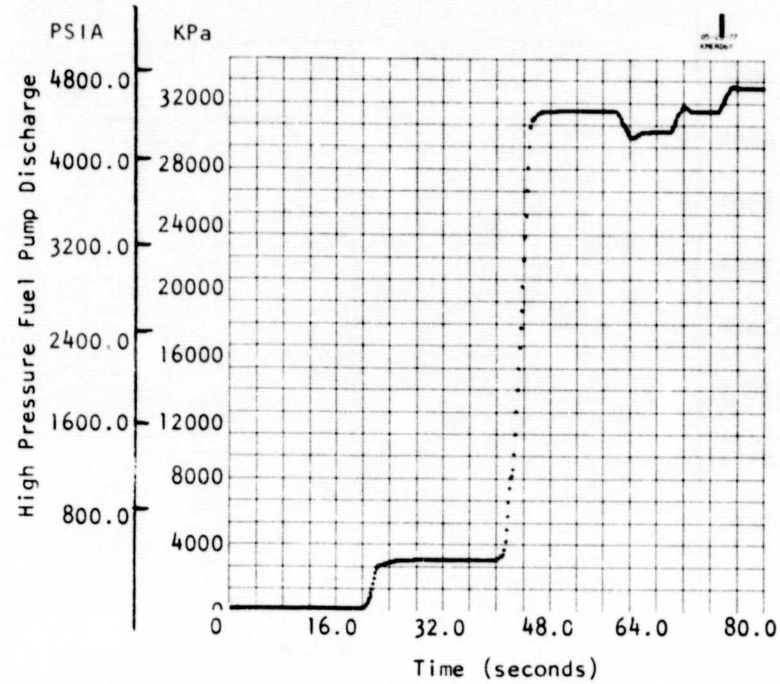

Figure 96. Fuel Pump Discharge Pressure vs Time (Summary)

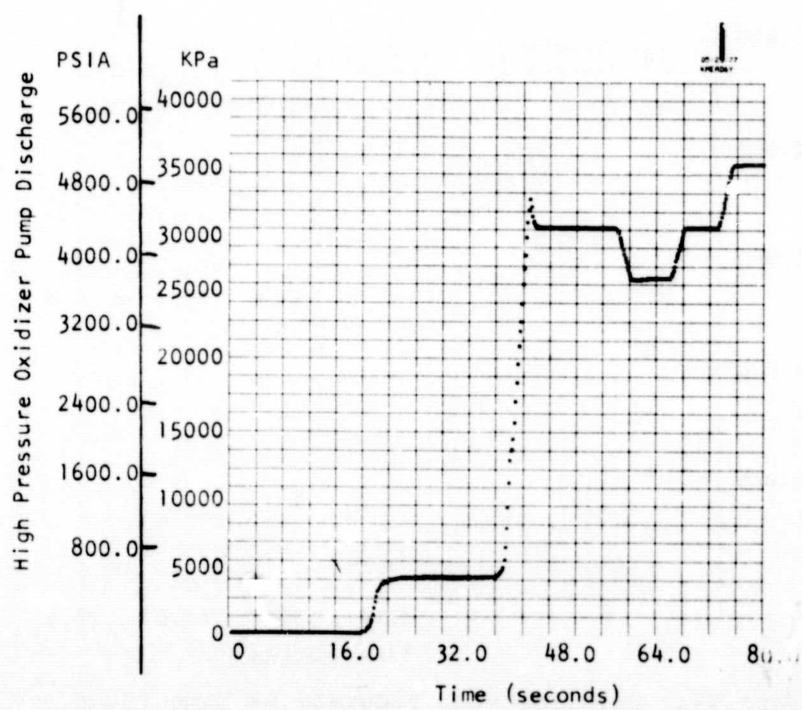

Figure 97. Oxidizer Pump Discharge Pressure vs Time (Summary)

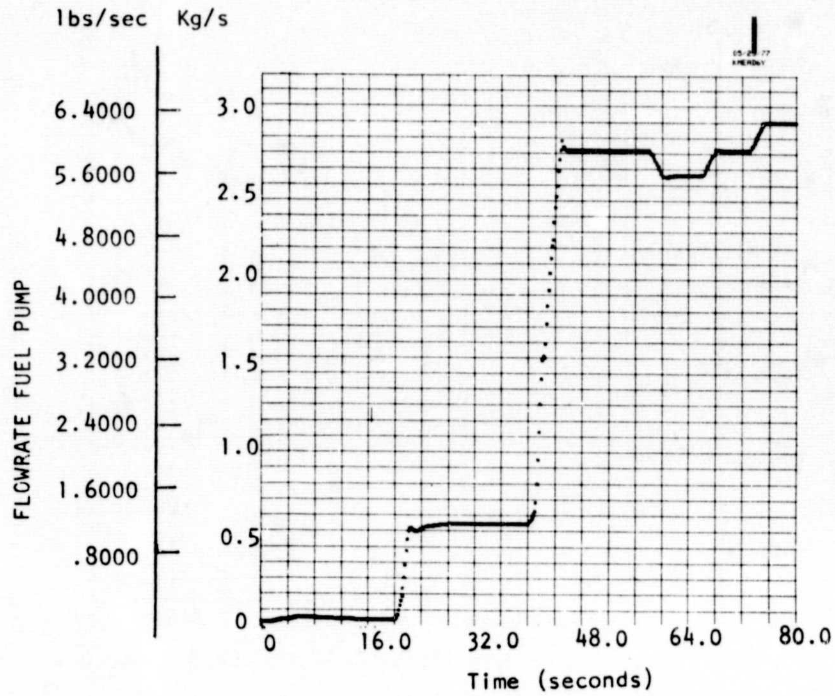

Figure 98. Fuel Pump Flowrate vs Time (Summary)

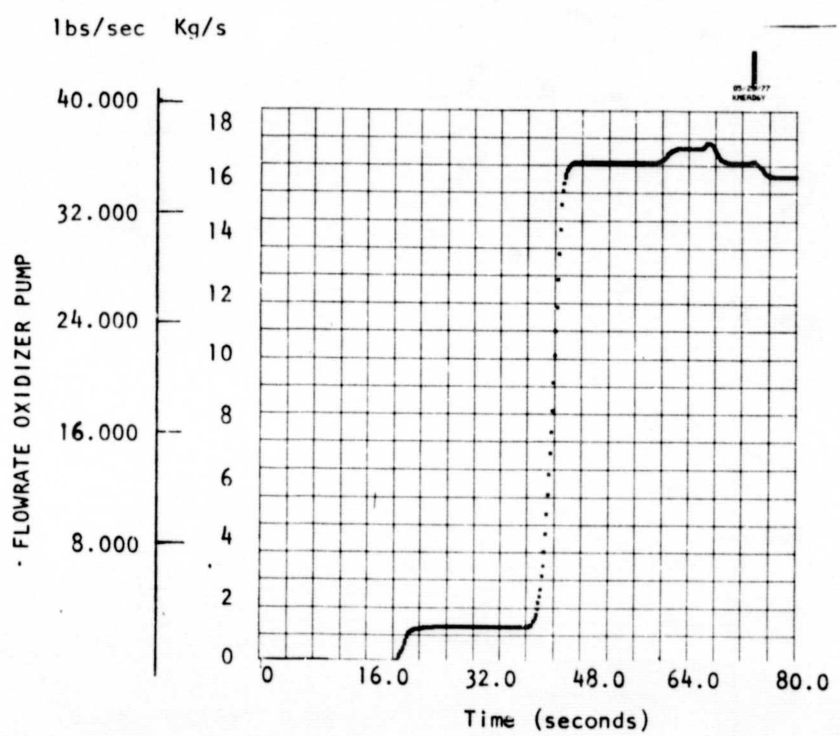

Figure 99. Oxidizer Pump Flowrate vs Time (Summary)

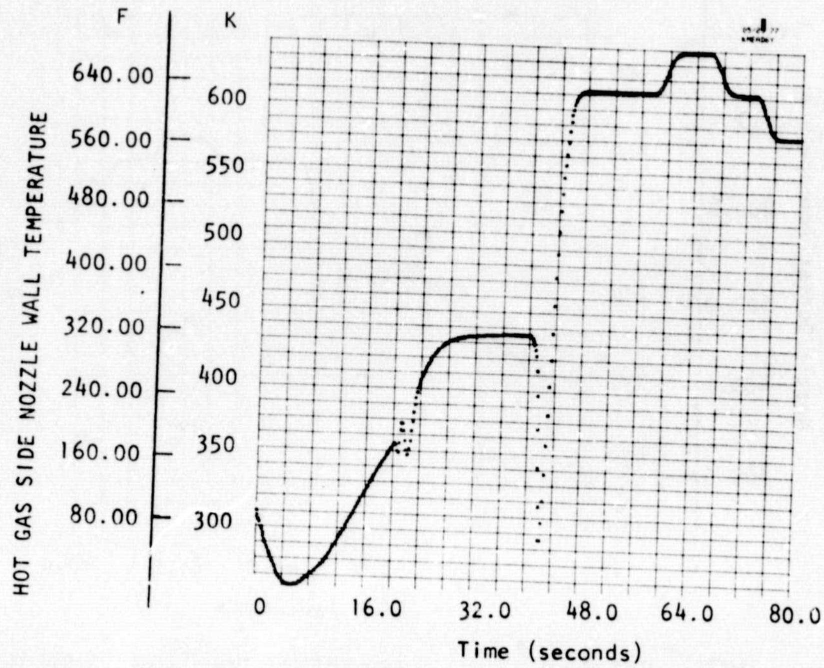

Figure 100. Hot Gas Side Nozzle Wall Temperature vs Time (Summary)

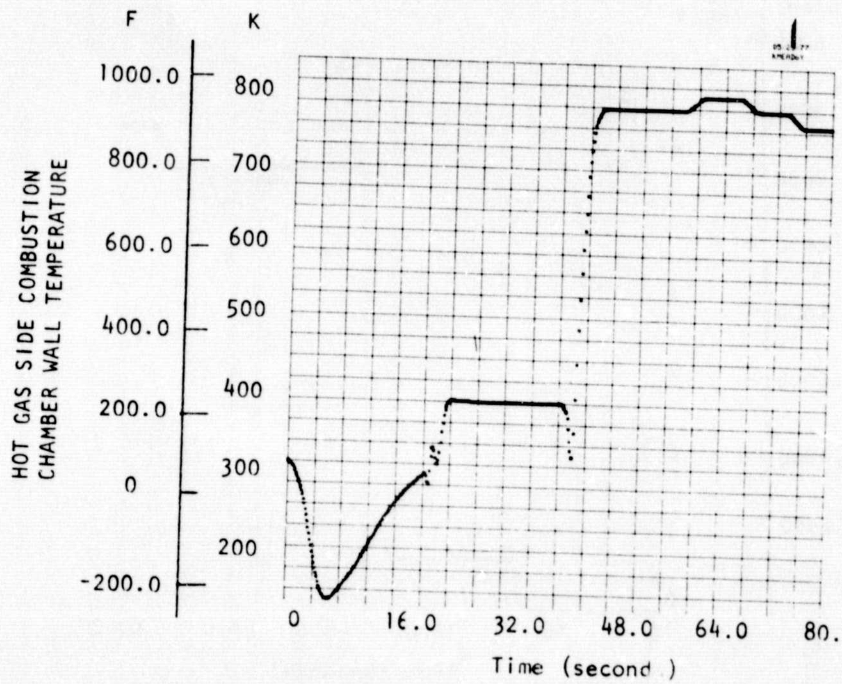

Figure 101. Hot Gas Side Combustion Chamber Wall Temperature vs Time (Summary)

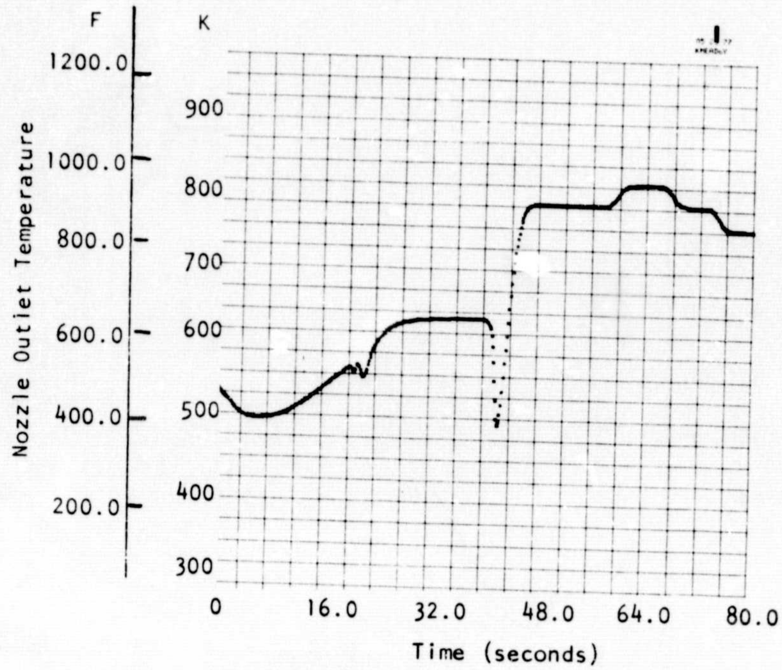

Figure 102. Nozzle Outlet Temperature vs Time (Summary)

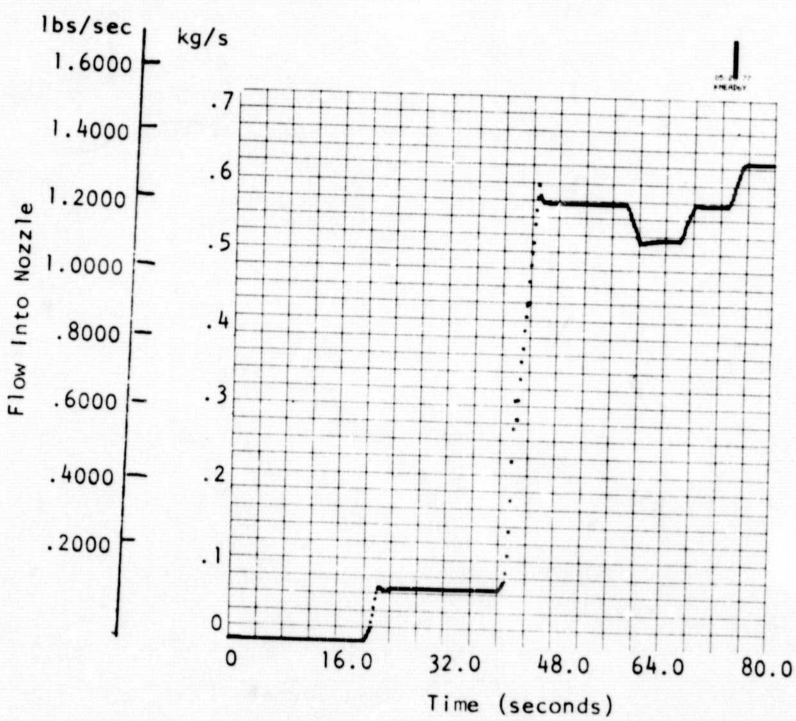

Figure 103. Flow Into Nozzle vs Time (Summary)

conditions. Unless a rapid tank pressurization system is developed, the tank head idle mode and pumped idle mode may be subject to inlet pressures of 551 kPa (80 psia) and 689 kPa (100 psia) instead of the 172 kPa (25 psia) inlets normal at tank head idle and the 231 to 310 kPa (35 to 45 psia) inlet pressures normal at pumped idle conditions. To determine the balance conditions for tank head idle and pumped idle mode, model runs were made using 551 kPa (80 psia) and 689 kPa (100 psia) inlet conditions. The results are presented in Fig. 104 and 105. Comparison with Fig. 10 and 11 shows significant changes at tank head idle mode. Chamber pressure increases from 61 kPa (9 psia) to 165 kPa (24 psia) and mixture ratio decreases from 2.0 to 0.85. Smaller changes occur in the pumped idle condition with chamber pressure increasing from 1289 kPa (187 psia) to 1392 kPa (202 psia) and mixture ratio changing very slightly from 2.03 to 1.93. Engine operation should be acceptable under any of the inlet conditions.

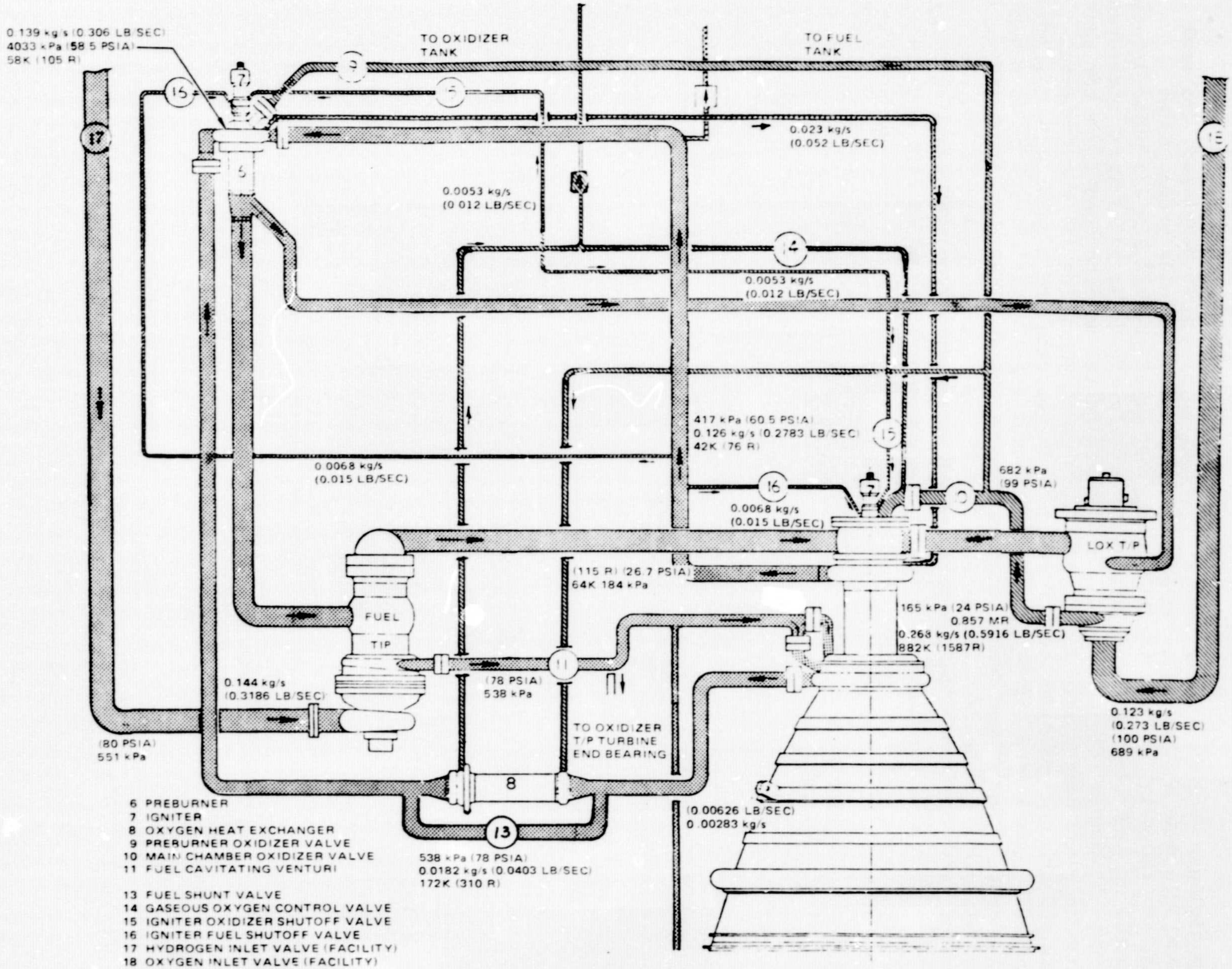

Figure 104. PBA System Tank Head Idle (high inlet pressures)

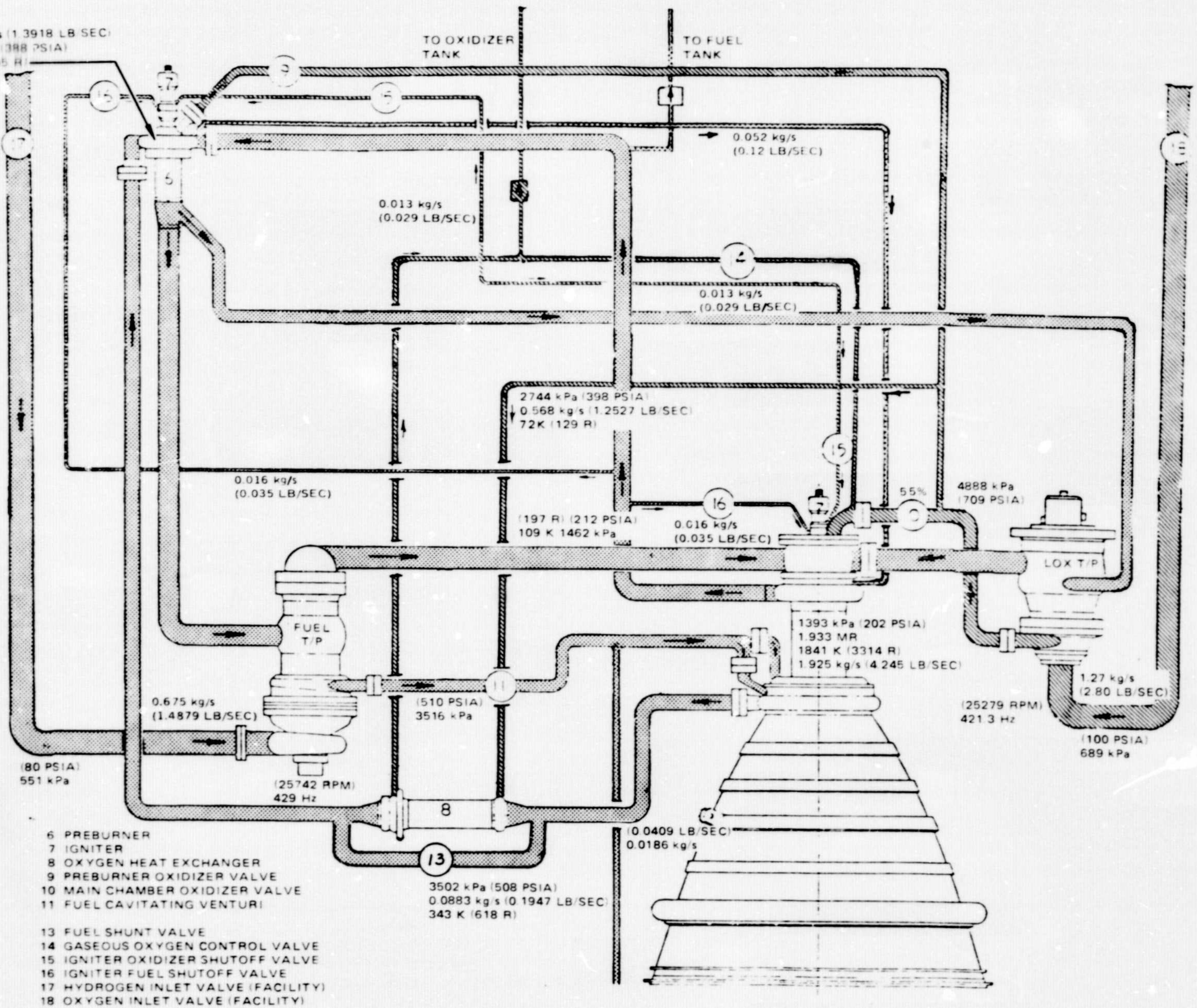

Figure 105. PBA System Powered Idle Mode (high inlet pressures)

CONTROL SYSTEM

CONTROL COMPONENTS

Requirements for all the valves of the system have been defined and are included in the specifications of Appendix A:

Specification Number	Components
ASE-1D	Preburner and Main LOX Valve
ASE-2B	LH_2 Suction and LOX Suction Valve
ASE-3C	Fuel Shunt Valve
ASE-4C	GO_2 Shutoff Valve
ASE-5B	GO_2 Ignition Valve
ASE-6B	GH_2 Ignition Valve
ASE-7B	Fuel Bypass Valve
ASE-8B	Main Fuel Valve
ASE-9A	GO_2 Throttle Valve
ASE-10A	GO_2 Check Valve
ASE-11	Electric Valve Actuator

Based on results of the mathematical model studies described in that section of this report, the fuel bypass valve and GO_2 throttle valve are not required and no valves have been selected. Using the specifications and the system configuration layout, the following valves were selected for PBA application.

Preburner and Main LOX Valves

Design layouts on the preburner and main LOX valves have been made using the specifications in Appendix A and are presented in Fig. 106, 107, and 108. Two valves are required for throttling oxygen flow to the ASE preburner and to the main injector for control of engine thrust and propellant mixture ratio. These valves must also shut off liquid oxygen flow and be fail-safe in the closed position.

The original design study which resulted in fabrication and testing of the two valves showed the maximum effective areas to be the following (Fig. 109):

1. Main LOX Valve - 2.081 cm^2 (0.3226 $in.^2$)

2. Preburner LOX Valve 0.696 cm^2 (0.1080 $in.^2$)

This study defined the valve geometry and sizing. The main LOX valve was defined as having a 12.1 mm (0.5 inch) holes in a 25.4 mm (1.0 inch) ball. The preburner LOX valve was defined with a similar geometry but with a ball size of 15.87 mm (0.625 inch) and a 7.62 mm (0.3 inch) hole. The main LOX valve was required to have a longer diffuser to meet pressure loss requirements. These valves functioned satisfactorily under test conditions.

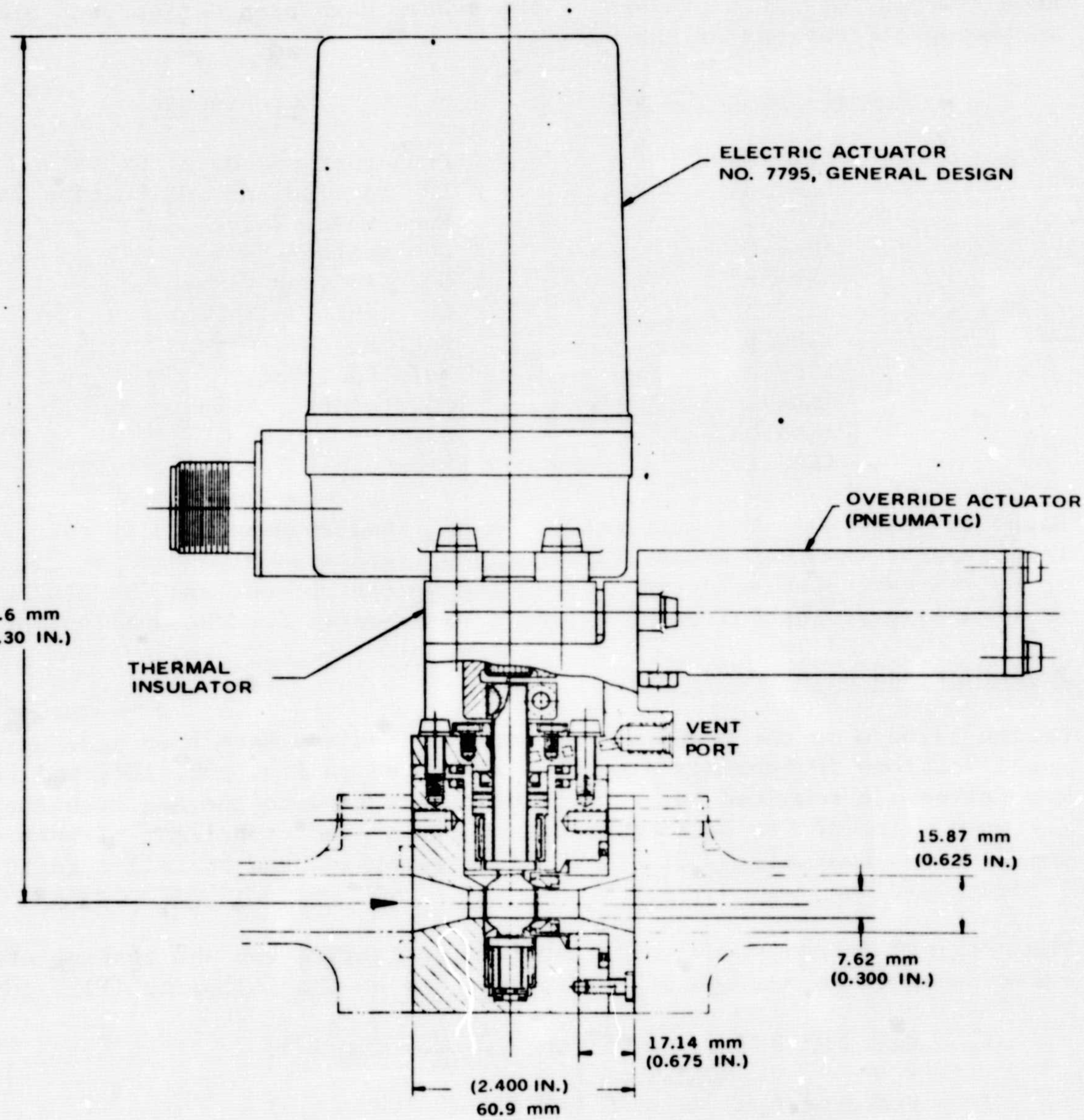

Figure 106. Preburner LOX Valve

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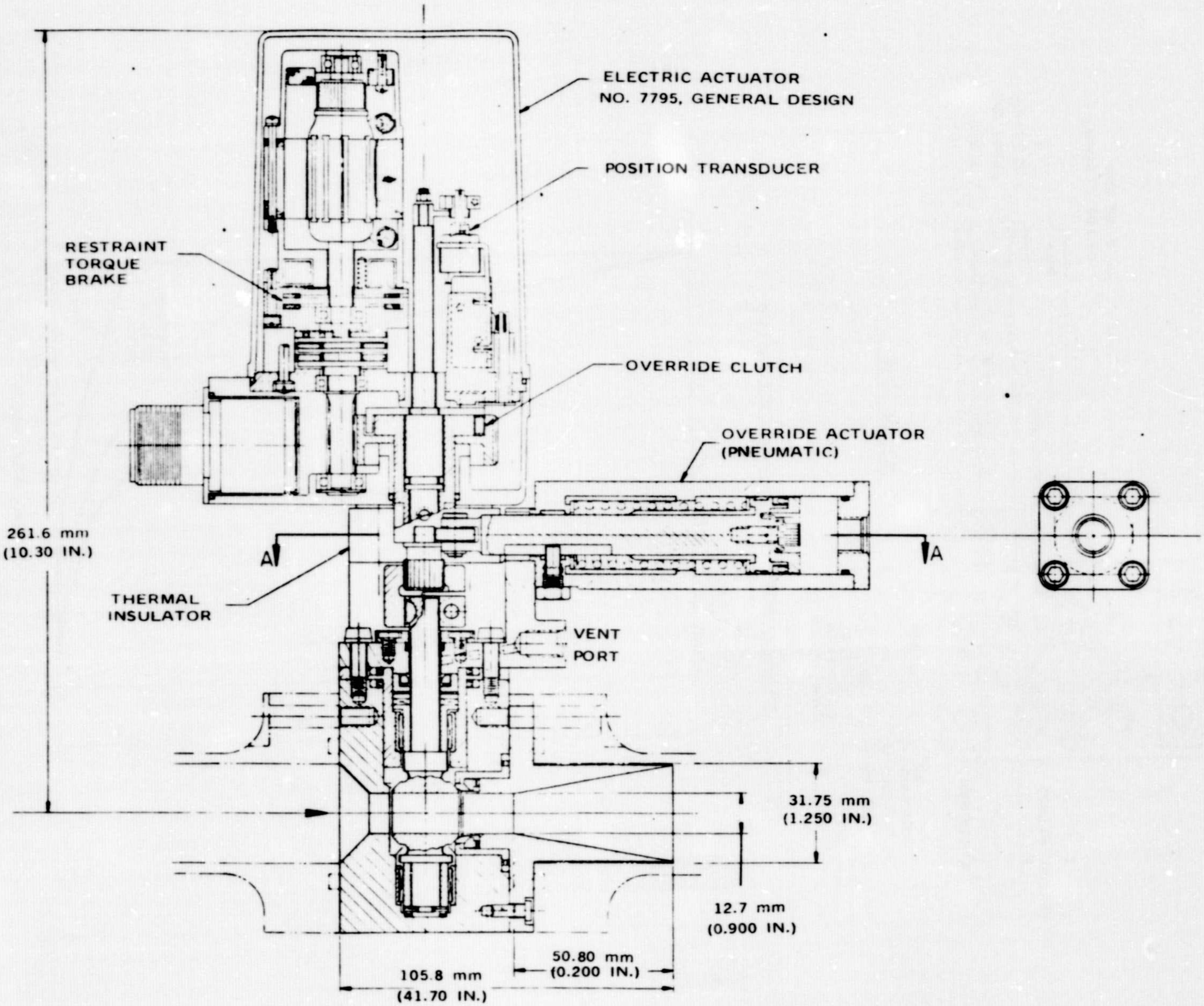


Figure 107. Injector LOX Valve

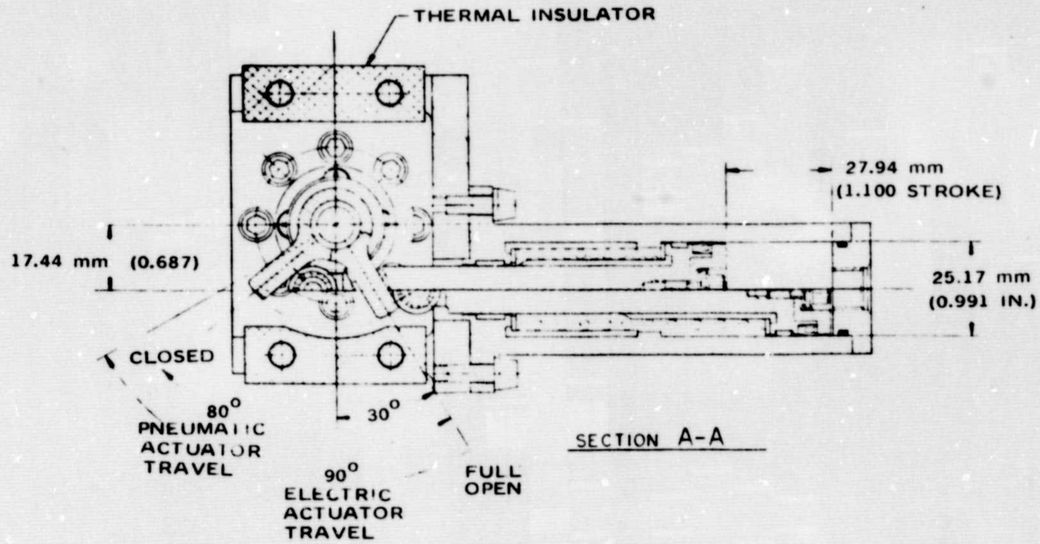


Figure 108. Injector LOX Valve

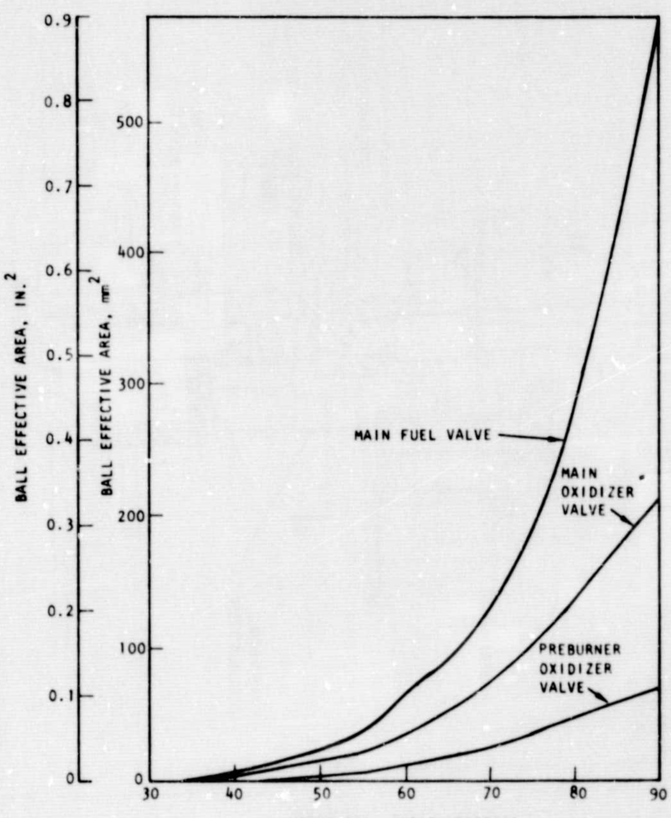


Figure 109. Valve Angle as Effective Area

The latest analysis for these valves incorporated slightly different pressure and flow requirements for the full-thrust condition based on the most recent steady-state balances. The ball valve computer program was then modified to calculate seal friction torque which must be overcome at different ball positions.

For the valve actuation system, a 28-volt electric motor flight hardware type actuator with electronics for any necessary power conversion and with a feedback position indicator will be used to provide linear motion to a rod. See Appendix A for the valve actuator specifications. The rod in turn is attached by a crank arm to the ball valve shaft to provide rotary motion. The motor must provide 890 Newtons (200 pounds) of force with a 25.4 mm (1 inch) moment arm to safely overcome fluid dynamic torque, ball seal friction, and shaft seal friction. The maximum ball seal friction was 2.48 and 5.65 N.m (22 and 50 in.-lbf) for the preburner and injector oxidizer valves, respectively (assuming a cavity pressure equal to the inlet pressure). The maximum shaft seal torque was found to be 1.13 N.m (10 in.-lbf) using the maximum inlet pressure. The dynamic fluid torque is always in the direction of closing and will thus oppose opening of the valve. The maximum dynamic torques are 0.373 and 6.33 N.m (3.3 and 56 in.-lbf) for the preburner and oxidizer valves.

The actuator must be able to close the valve at the end of the engine run if the power to the motor is lost or if the motor locks. Thus, a pneumatic override will be used. The pneumatic supply pressure assumed available is to be 2757 kPa (400 psi). This pressure will only be supplied if a solenoid is actuated. The solenoid may be a latching type which will stay open once actuated and powered by a stored energy source such as a charged capacitor bank. The pneumatic override will have its own actuator rod which will be pinned to the main actuator rod, which will require the override to only overcome friction forces and a spring force instead of trying to move the motor. This will reduce the force requirements of the override system.

Main Fuel Valve

The design layout for the main fuel valve is presented in Fig. 110 for the specification in Appendix A.

The main ASE fuel valve serves a dual function in engine operation. Located just downstream of the main fuel pump discharge, the main fuel valve can provide modulation of fuel flow as well as isolation of the fuel pump from pressure oscillations caused by boiling instability in the regeneratively cooled thrust chamber during the alternate tank head idle. The later function is provided by using a cavitating venturi.

Analysis of the required valve operating characteristics indicated that a ball valve similar to the LOX preburner and main injector valves could be used in this application. Either a separate commercially available venturi could be used as a bypass around the main fuel valve, or the valve itself could be modified by removing the seals to provide a cavitating venturi effect.

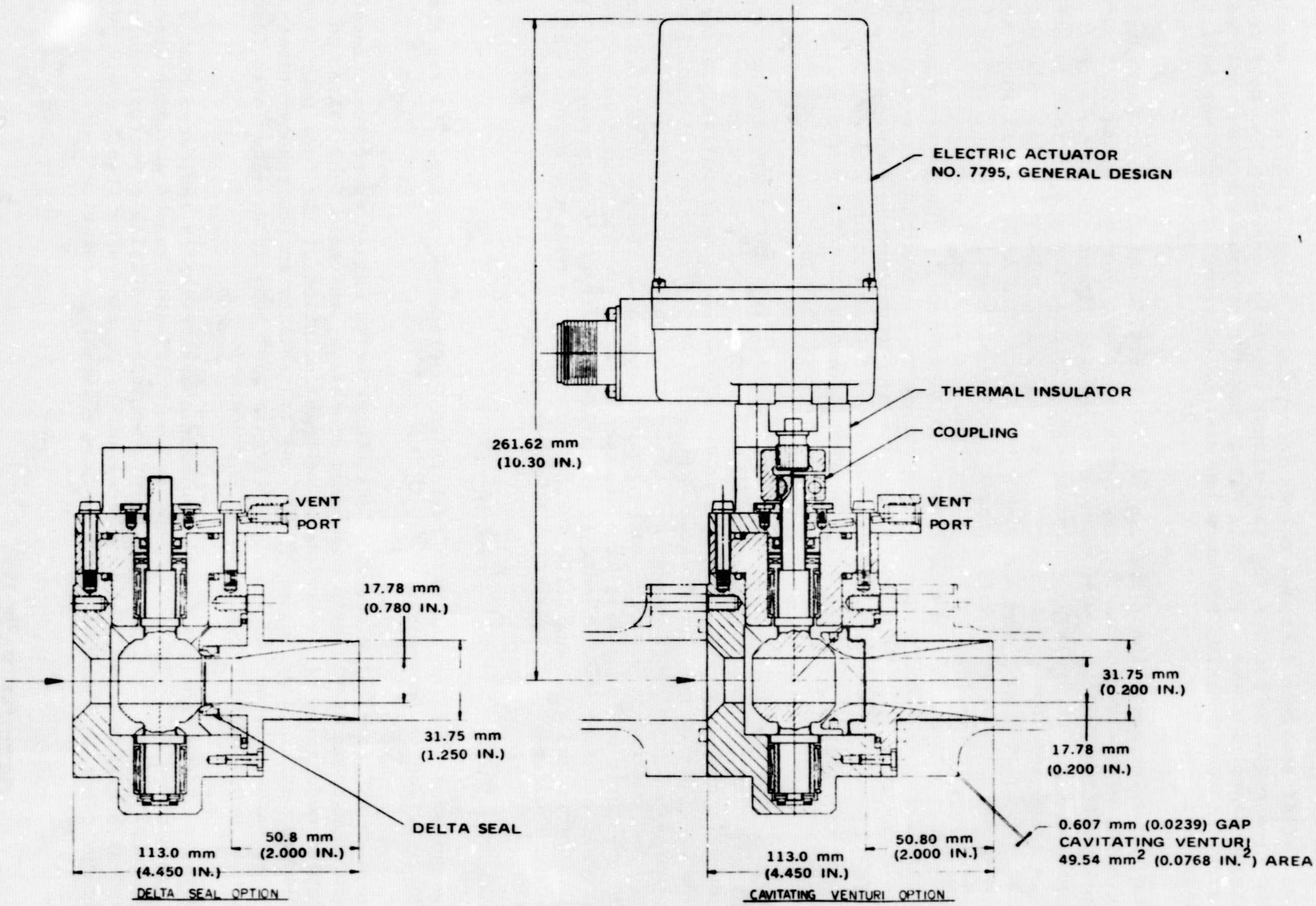


Figure 110. Main Fuel Valve

A parametric design study using the ball valve computer program showed that a 38.1 mm (1.5 inch) ball with a 17.78 mm (0.7 inch) hole will be more than adequate. One hundred percent flow through the main fuel valve was assumed, and the inlet pressure used was slightly less than the fuel pump discharge pressure to account for line losses. The nominal maximum effective flow area will be achieved at a position angle of 84 degrees, and the minimum required ball rotation to close the valve to the cavitating position is 56 degrees.

The valve could act as cavitating venturi when in a closed position by removing the ball seal and utilizing the resulting gap flow. Adding a ring to the outlet flange will provide a rounded corner so that the venturi will have a good pressure recovery as shown in Fig. 111. The corner radius was tentatively chosen to be the same as the ball radius to provide a symmetrical flow channel. The minimum gap width to provide the required venturi area of (48.90 mm^2 (0.0758 $in.^2$) is 0.607 mm (0.0239 inch) for a flow coefficient of 0.93. The ring will screw on to the outlet flange as shown in Fig.112. Annular shims can be added to adjust the gap between the corner and ball to allow for errors in manufacture and changes in flow requirements.

The upstream gap must be larger than the downstream to prevent excessive pressure loss before reaching the venturi. A gap of 0.9 to 2.54 mm (0.075 to 0.100 inch) should be adequate. During full thrust, the actual effective area of the valve will be larger due to the gap flow. (This effect was not included in the computer analysis.)

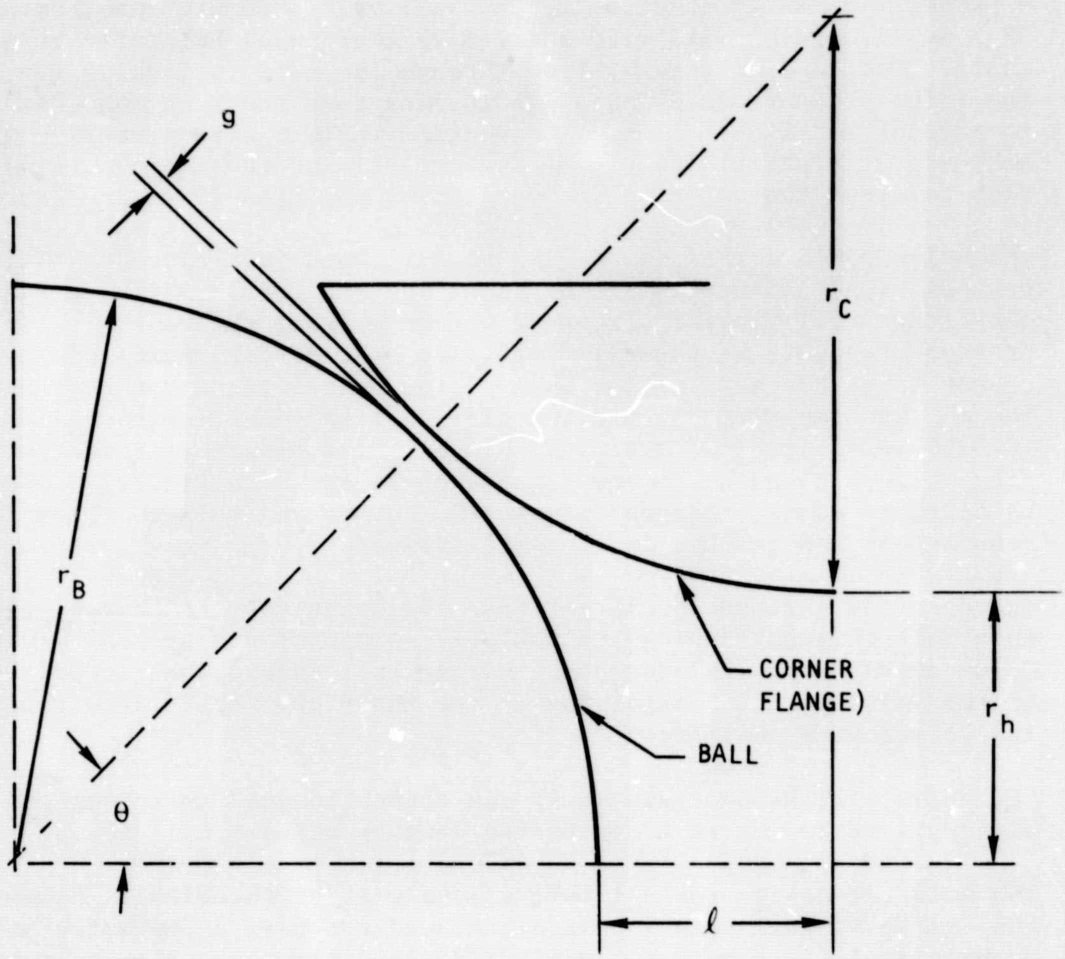
The valve will be designed so it can either be used as a complete shutoff valve with ball seals, or as a cavitating venturi without ball seals.

The actuator design for all ball valves will be identical. However, the main fuel valve is fail-safe in place and need not have a pneumatic override. The dynamic analysis showed the maximum dynamic flow torque to be 6.558 N.m (58 in.-lbf). Only the friction torque of 1.13 N.m (10 in.-lbf) at the shaft seal must be overcome in the main fuel valve if there is no ball seal.

LH_2 and LOX Suction Valves

The powerhead breadboard assembly has a requirement for positive shut off valves on the inlet low-pressure sides to the LO_2 and LH_2 turbopumps. For the breadboard engine existing, J-2 engine fuel valves (P/N 409920) shown in Fig. 113 will be used. These valves are available and have been reserved for engine support. The calculated pressure drop for the valve at rated engine flow is 1.999 kPa (0.29 psid) and 1.03 kPa (0.15 psid) for the LO_2 and LH_2 sides, respectively.

For the ASE flight design requirements listed in the specification in Appendix A, a ball valve is recommended, based on the low-pressure-drop characteristics for a given flow diameter and also for compactness of design. A similar ball valve has been designed and tested for the LOX preburner and injector valves. The valve will be two-positioned pneumatic opened and pneumatic and/or spring closed with an actuator designed for the closed fail-safe position.



(1) $\ell = (r_B + r_C + g)\cos\theta - r_B$

(2) $\theta = \sin^{-1}[(r_H + r_C)/(r_B + r_C + g)]$

r_B = BALL RADIUS
r_C = CORNER RADIUS
r_H = HOLE OR INLET RADIUS

q = 0.607 mm (0.0239 IN.); θ = 46.206 DEGREES; ℓ = 7.737 mm (0.3046 IN.); r_H = 8.889 mm (0.35 IN.); $r_C = r_B$; AND r_B = 19.05 mm (0.75 IN.)

Figure 111. Cavitating Venturi Valve Cross Section (Scale 4:1)

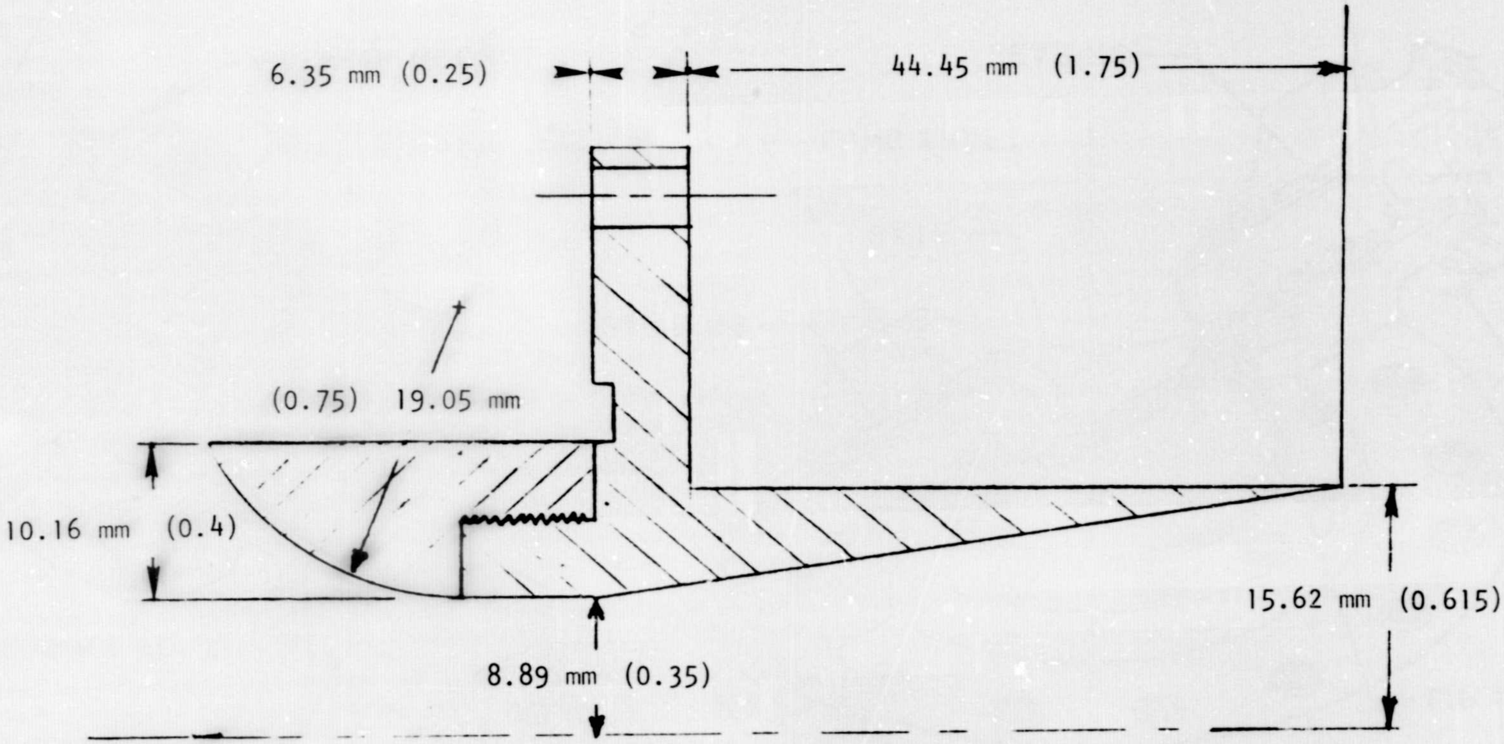


Figure 112. Main Fuel Valve Outlet Flange and Venturi Ring

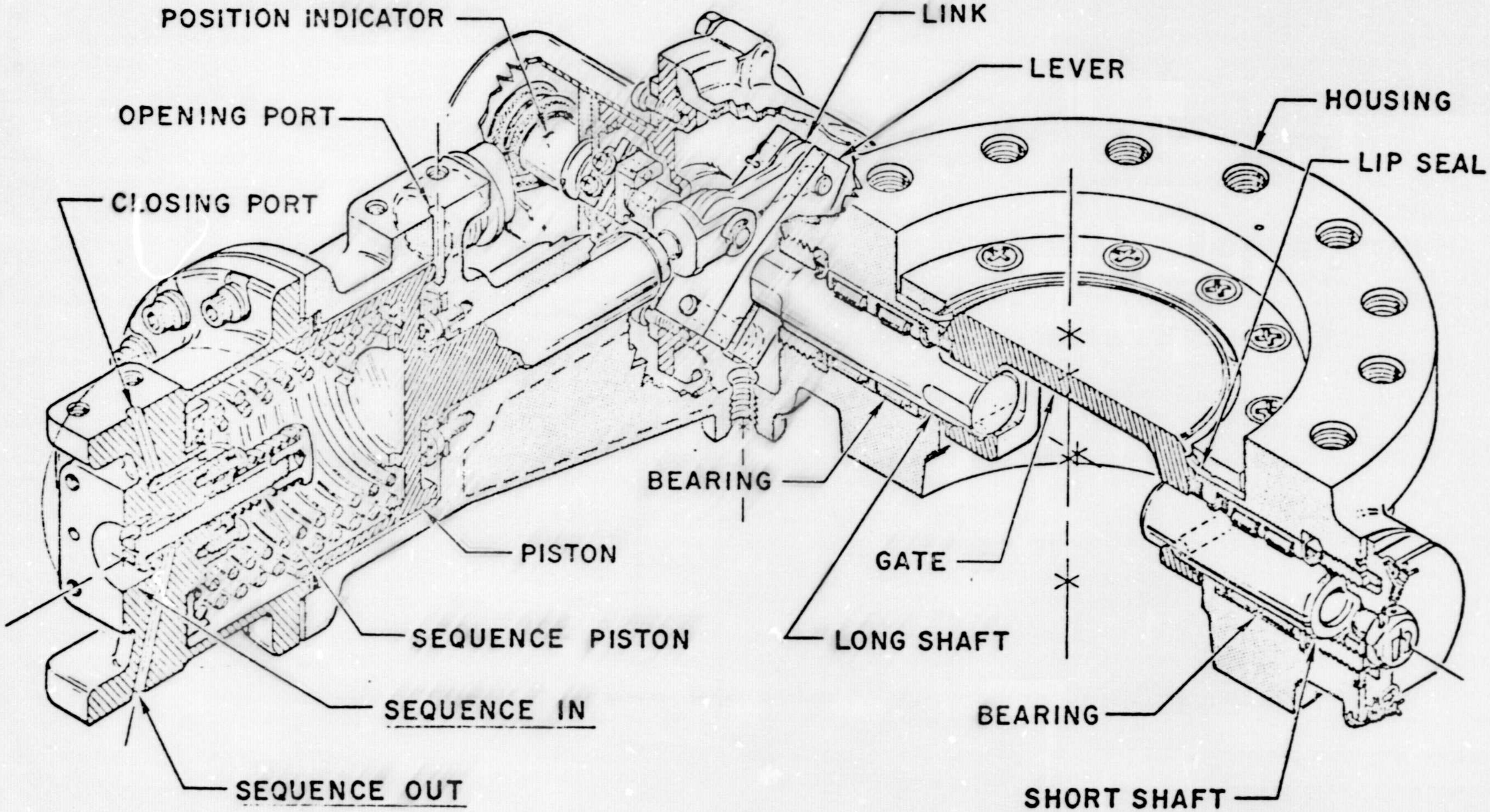


Figure 113. Main Fuel Valve Isometric

The use of a single solenoid valve for controlling opening and closing of both suction valves is recommended to prevent out of sequence opening/closing of either valve during failure condition. In the vent of an emergency shutdown, both valves would close with one signal. The control solenoid valve could be mounted directly to one of the valve actuators and a line connected to the other actuator for common operation.

Figure 114 shows the curve of valve flow diameter versus valve ΔP. For a 6.89 kPa (1 psi) ΔP, the valve sizes are 43.18 mm (1.70 inches) and 49.53 mm (1.95 inches) for the fuel and oxidizer valves, respectively.

GOX Shutoff Valve

The original specification included a single valve which had three functions:

1. Control of GOX flow to the oxidizer tank pressurization supply
2. Control of GOX flow to the main LOX injector during tank head idle
3. Control of mixture ratio during tank head idle by servo-control of the flow

In the final PBA configuration, the control of GOX pressurization flow to the main tank is provided by a simple check valve which meets the requirements of the specification in Appendix A. Mathematical model studies indicate that mixture ratio control during tank head idle is not required which negates the servo flow control requirement. Deleting the first and third function leaves a requirement for a simple shutoff valve open during tank head idle and closed the remainder of the time.

For the application, either a ball or poppet type valve would be satisfactory. Sizing information based on the specification is presented in Fig. 115. For the PBA application, a 19-mm (3/4 inch) tube size 2-way solenoid valve would satisfy the requirements if modified for cryogenic operation by replacing all "O" rings with cryogenic seals and providing a stainless-steel body for the higher pressure rating 41 368 kPa (6000 psi). This design is pilot operated and normally requires 172 kPa (25 psig) minimum to open; however, the operating pressure range can be extended down to zero psig on request. The 19-mm (3/4 inch) tube size valve has an equivalent sharp edge orifice diameter (ESOD) of 15.2 mm (0.600 inch) for a Cd of 0.6. The valve ΔP would be slightly less than 34 kPa (5 psig) at rated flow (use poppet valve curve on Fig. 115).

For the flight engine, a two-position penumatically actuated ball valve could satisfy the operating requirements. The advantage of a ball valve is compactness in size and low pressure drop. The disadvantage is the requirement for a separate pneumatic supply, including solenoid valve, to operate the valve.

The preburner LOX ball valve design could be modified for the GO_2 shutoff valve. This would require modification to provide a pneumatic actuator, in place of the electric actuator, for valve actuation.

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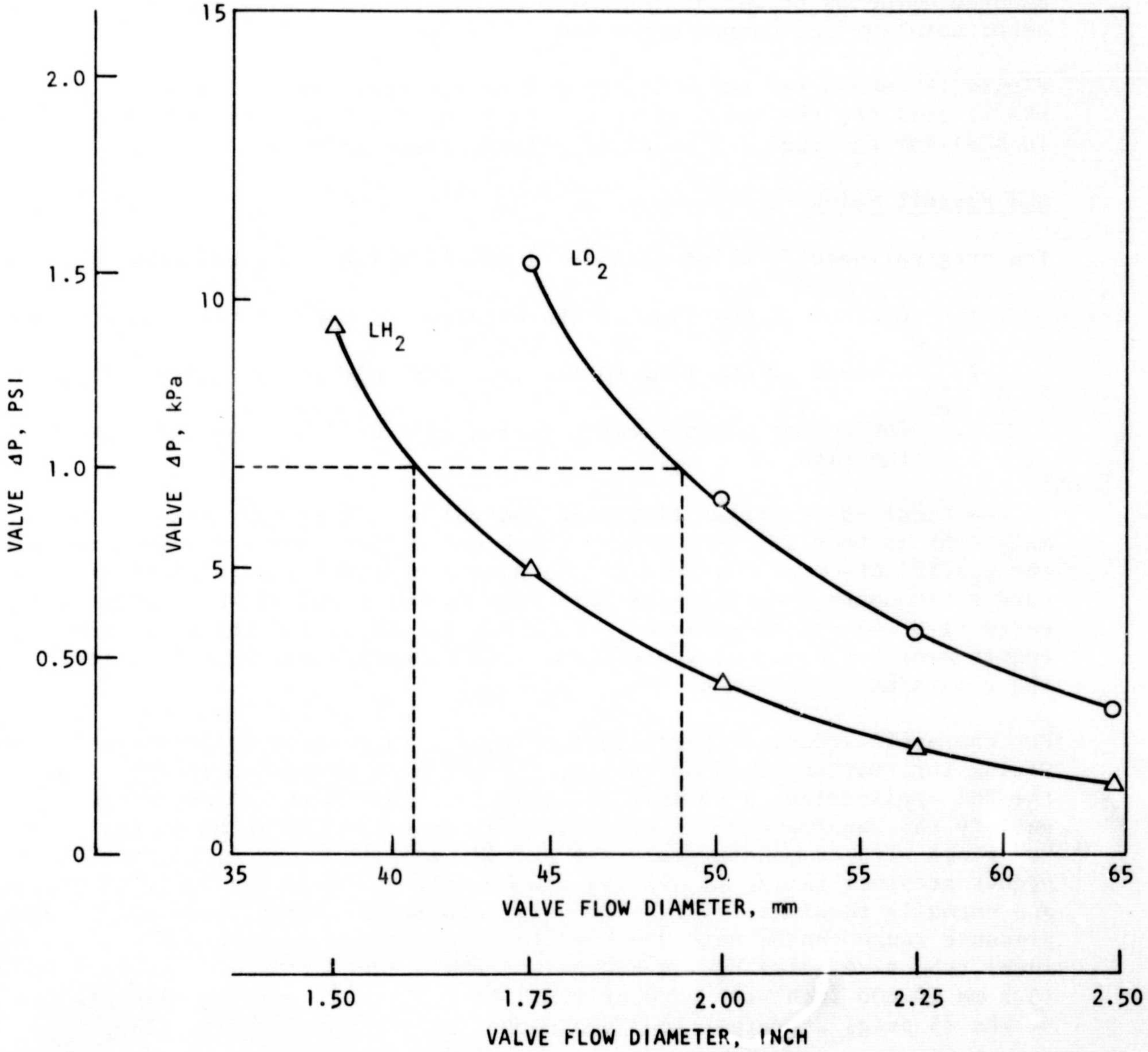


Figure 114. Suction Valve Size vs ΔP (Design Requirements for ASE)

C-2

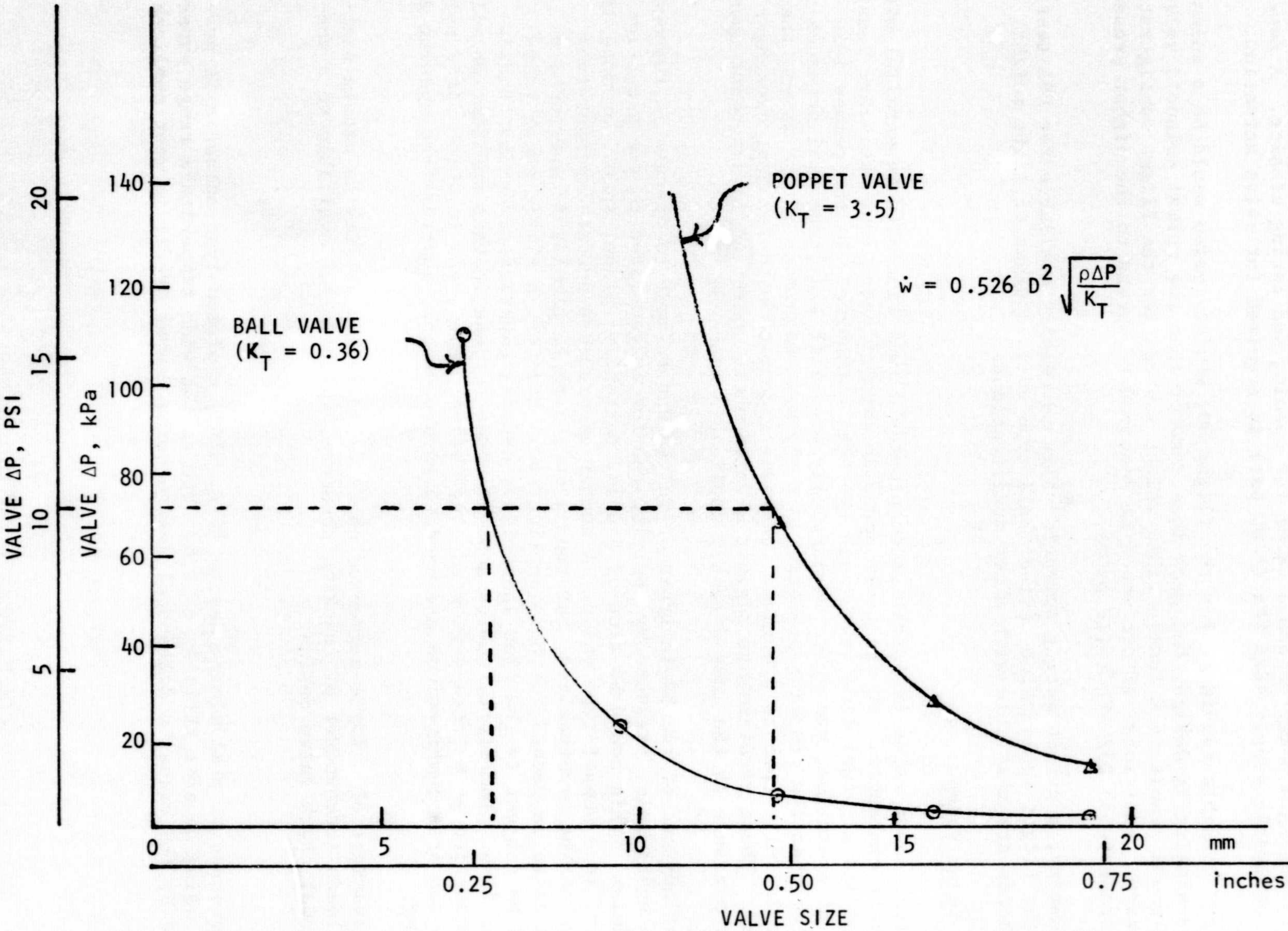


Figure 115. Valve ΔP vs Flow Diameter ASE GO_2 Shutoff Valve

Another approach for a ball valve would be a commercial type cryogenic valve incorporating a 3-way solenoid valve for opening and spring closing. A separate penumatic supply 4826 kPa (≈700 psi) is required for valve actuation.

Another possible candidate for the flight GO_2 shutoff valve would be a solenoid valve similar in design, but much more compact than the normal solenoid valve. This would result in a considerable weight savings for the flight configuration hardware. Additional effort would be required to uprate to the higher pressure requirements 35 232 kPa (5110 psig).

In summary, a direct acting solenoid valve is readily available for PBA testing. For the flight application, either ball type valve designs or light weight solenoids are available with minor modifications.

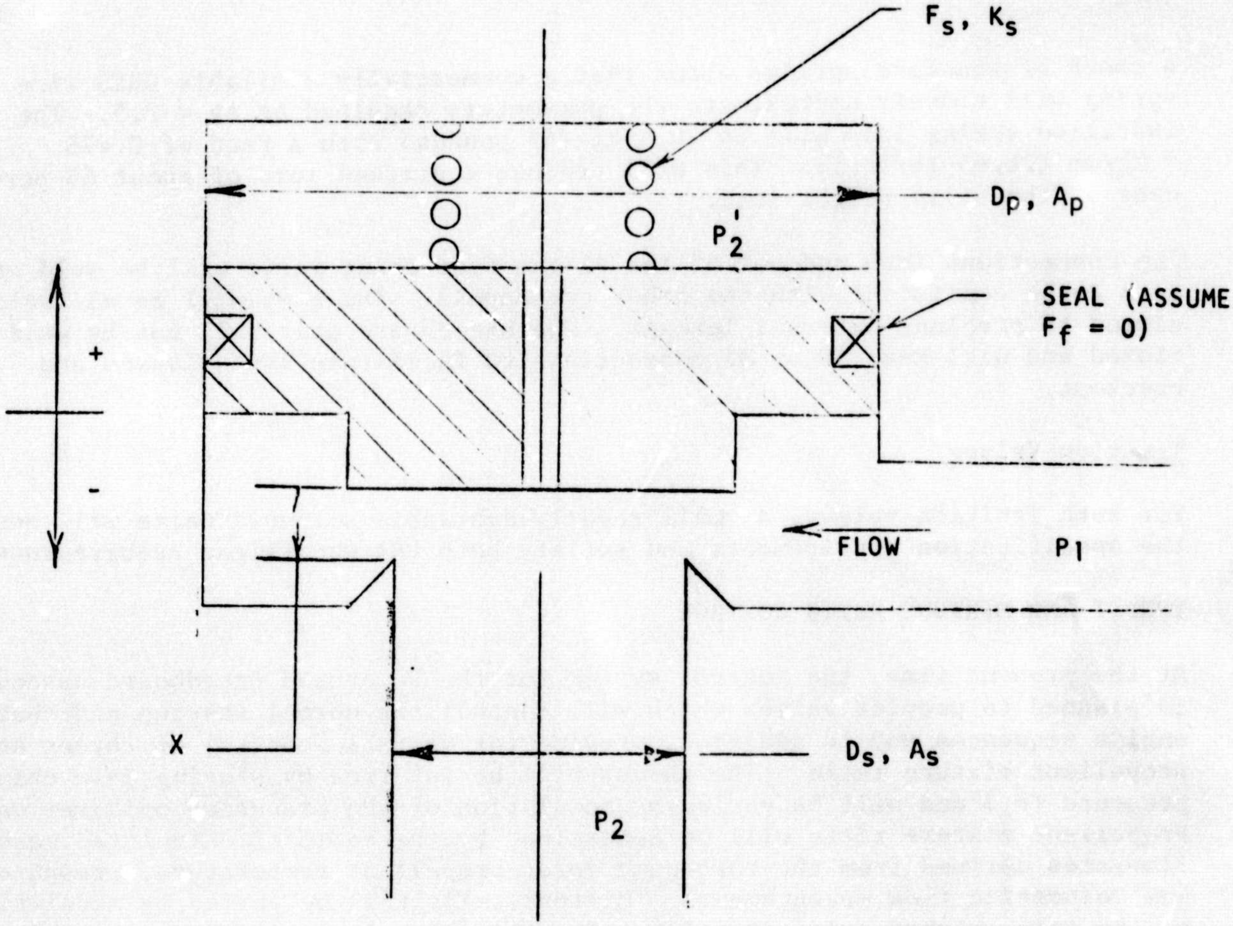
Fuel Shunt Valve

The fuel shunt valve is installed to provide a fuel flow path in parallel with the heat exchanger. In the tank head idle mode of operation, the valve remains closed and all fuel flow is through the heat exchanger. In the pumped idle mode of operation, the valve is partially open with a differential pressure greater than the cracking pressure. In the mainstage mode of operation, the valve is fully open to provide a low-resistance flow path for heat exchanger bypass. These requirements suggest a valve whose operation is dependent upon inlet pressure is the most directly applicable approach.

Almost any one of the basic types of valves can be made to operate in response to changing inlet pressure by applying the forces generated to the actuation mechanism. This could be true of a ball, butterfly, blade, spool, or more directly, to a poppet-type valve. A number of pressure-actuated poppet-type valves can be hypothesized, but from a most direct, simplistic approach, a check valve is needed for this application. However, a simple check valve would be subject to the flow instability usually experienced during transitional flow. Therefore, the concept proposed for use in this application will be identified as a force-augmented check valve; it.e., one in which fluid pressures and area combinations are used to ensure smooth, chatter-free opening and closing.

The advantage of a force-augmented check valve is its ability to obtain seat-seal loads independent of cracking pressure, which is not available to a conventional check valve design.

For purposes of preliminary design (Fig. 116), a piston-type actuator is proposed using an area ratio A_R of 3.5. Due to the wide temperature range experienced by the valve, a delta-seal design using Vespel SP-211 is most applicable.



F_s = SPRING FORCE
K_s = SPRING RATE
X = STROKE
D_p = PISTON DIAMETER
A_p = PISTON AREA
D_s = SEAT DIAMETER
A_s = SEAT AREA
P_1 = INLET PRESSURE
P_2 = OUTLET PRESSURE
F_f = FRICTION FORCE, SEAL
$A_p/A_s = A_R$, AREA RATIO
$P_1 - P_2 = \Delta P$, VALVE DELTA PRESSURE

Figure 116. Fuel Shunt Valve

The seat and poppet should be flat metal-to-metal, fine-grain tungsten carbide for long wear, and lapped to approximately a √ finish. The seat is preliminarily specified as 0.254 mm (0.010 inch) wide with an ID of 17.14 mm (0.675 inch).

A check of standard springs shows that a commercially available CRES wire spring will closely approximate the parameters required at A_R = 3.5. The installed spring load will be 20.4 kg (45 pounds) with a rate of 0.475 9 kg/mm (26.65 lb/inch). This will produce a stroked load of about 83 percent of the solid height load.

The connections into and out of the flight fuel shunt valve will be weld stubouts to be consistent with the other components. The body will be all weld closed to preclude external leakage. The breadboard unit will not be weld closed and will have AN or MS connections to facilitate installation and checkout.

Ignition Valves

For both ignition valves, a small readily available solenoid valve will meet the specification requirements and satisfy both PRA and flight requirements.

THRUST AND MIXTURE RATIO CONTROL

At the present time, the control system for the Powerhead Breadboard Assembly is planned to provide valves which will control the normal startup and shutdown engine sequences and in addition, provide for variable control of thrust and propellant mixture ratio. The thrust will be inferred by sensing main chamber pressure (P_c) and will be varied by modulation of the preburner oxidizer valve. Propellant mixture ratio will be determined by the ratio of calculated mass flowrates derived from the turbopump inlet propellant temperature, pressure, and volumetric flow measurements. Mixture ratio will be varied by modulation of the main chamber oxidizer valve. The control valves will have electrical interfaces and incorporate position switches or indicators per the attached Table 8.

The instrumentation transducers used to provide signals to the controls system will have characteristics as listed in Table 9. Inasmuch as present planning is to have all instrumentation transucers provided as facility equipment, no interface connector information is listed. It is planned to locate the controller(s) for thrust and mixture ratio in the control center with the signals available in that location.

TABLE 8. VALVE PBA CONTROL SYSTEM

Item	Actuation			Position Instrumentation			Electrical Connector Mate	
	Pressure	Electric Motor	Electric Solenoid	None	2 Position	Resistance Potentiometer	Type	Pin Assignment
LOX Suction Valve	X				X		MS-3106-16S-13	D (closed); E (common); F (open)
Fuel Suction Valve	X				X		MS-3106-16S-13	D (closed); E (common); F (open)
Suction Valves Pilot			X	X			MS-3106-12S-3S	A (+); B (-)
Fuel Bypass			X	X			MS-3106-12S-3S	A (+); B (-)
Preburner Oxidizer		X				X	MS-3106-MS-1S	A (+) CCW; C (-) (+); B CW; E POT; D CTR; F POT; and G NC
Main Oxidizer		X				X	MS-3106-MS-1S	A (+) CCW; C (-) (+); B CW; E POT; D CTR; F POT; and G NC
Main Fuel		X				X	MS-3106-MS-1S	A (+) CCW; C (-) (+); B CW; E POT; D CTR; F POT; and G NC
Preburner Igniter Oxidizer			X	X			Tite flex	
Preburner Igniter Fuel			X	X			HOS-7-S18 3	
Main Chamber Igniter Oxidizer			X	X			HOS-7-S18 3	
Main Chamber Igniter Fuel			X	X			HOS-7-S18 3	
GO_2 Shutoff Pilot			X	X			MS-3106-12S-33	A (+) and E (-)

TABLE 9. INSTRUMENTATION PBA CONTROL SYSTEM

Parameter	Transducer	Output Signal Characteristics
Main LOX Flow	Turbine flow meter	Pulse rate proportional to volumetric flowrate
Main Fuel Flow	Turbine flow meter	Pulse rate proportional to volumetric flowrate
LOX Temperature at F/M	Platinum RTB	Low level D.C. proportional to temperature
Fuel Temperature at F/M	Platinum RTB	Low level D.C. proportional to temperature
LOX Pressure at F/M	Strain gage bridge	Low level D.C. proportional to pressure
Fuel Pressure at F/M	Strain gage bridge	Low level D.C. proportional to pressure
Main Chamber Pressure	Strain gage bridge	Low level D.C. proportional to pressure

As indicated in Fig. 117, the controller includes function generators which deliver weight flowrate output signals in response to volumetric flowrate input signals, supplemented by flowmeter inlet pressure and temperature signals. A ratiometer delivers a propellant weight flowrate mixture ratio signal, for comparison with an externally commanded mixture ratio input signal.

An integrating amplifier, with lead-lag compensation features, responds to eliminate mixture ratio error, and delivers a main injector oxidizer ball valve angular-position command signal. This signal is compared with a valve position feedback signal. Position error is the input to a proportional amplifier that delivers a current to the valve electric motor actuator. The motor is self-holding, and the current reduces to zero when the position error is less than a small preset value. When the position error exceeds the small preset value, the current has a minimum value that is sufficient to ensure actuator motion in the presence of a self-holding restraining torque.

Thrust control is achieved by comparing a thrust chamber pressure signal with an externally commanded reference pressure signal. The commanded pressure signal is a calibrated function of thrust. An integrating amplifier, with lead-lag compensation features, responds to eliminate pressure error, and delivers a preburner oxidizer valve angular-position command signal. The valve position control loop is identical to that for the main injector oxidizer valve. Control

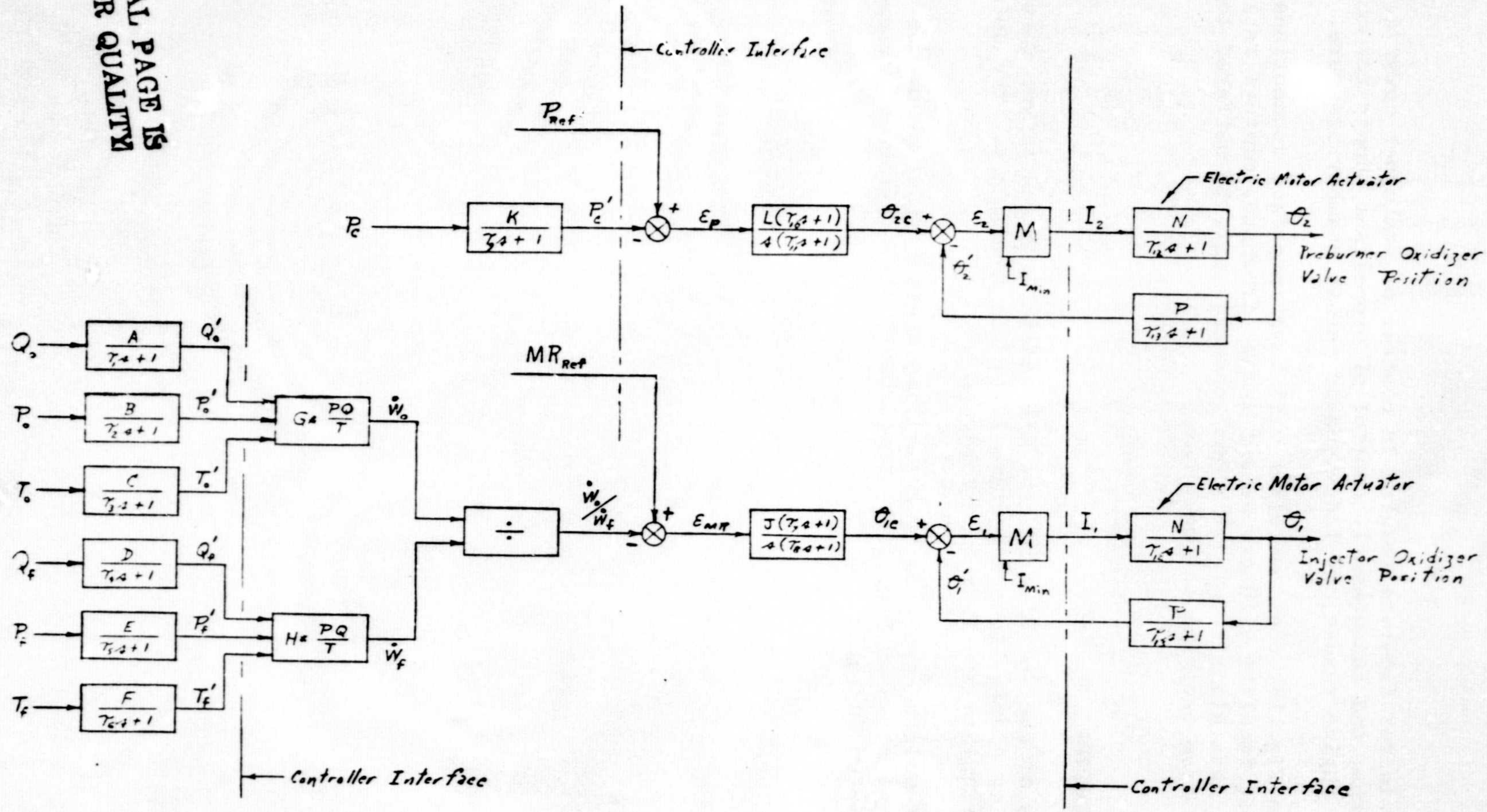


Figure 117. PBA Control Loops Block Diagram

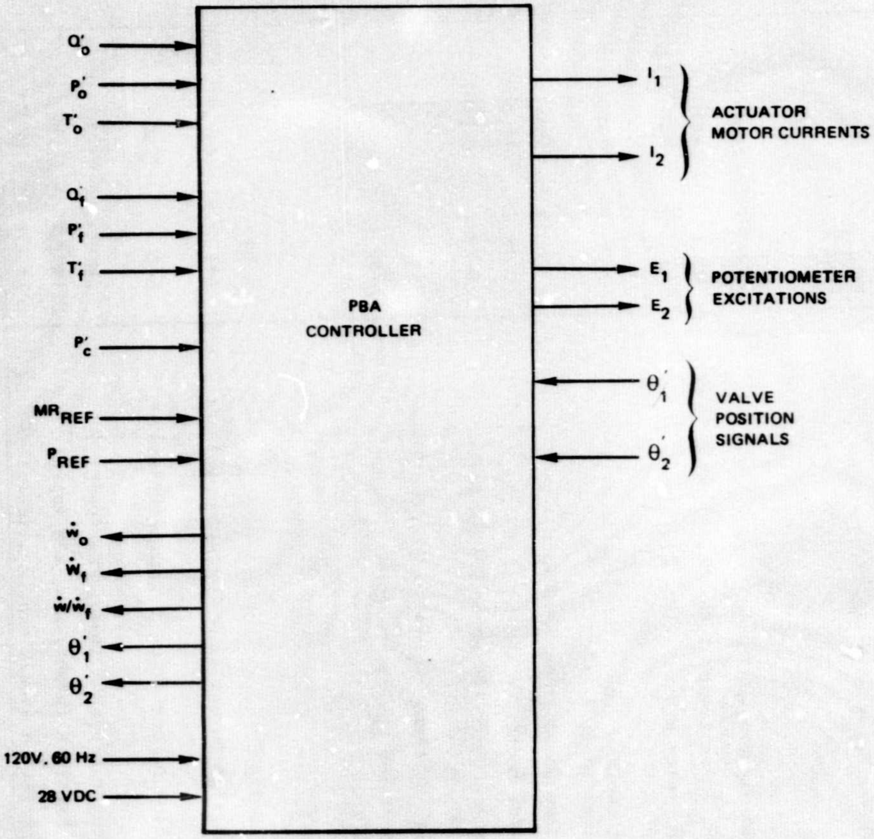
of preburner oxidizer flowrate results in control of preburner power delivery to the turbopumps, and consequently control of propellant supply for combustion and control of engine thrust, as indicated by thrust chamber pressure.

As indicated in Fig.118, the controller will have interface connections to provide the test facility with propellant weight flowrate, mixture ratio, and valve position data signals. These signal channels will be buffered to protect the controller from external malfunctions.

FACILITY REQUIREMENTS

The requirements of the facility to test the PBA include sufficient instrumentation capability to provide the parameters listed in Appendix B. The automatic cutoff devices required are listed in Table 10.

Valve sequencing will be provided by a facility digital event sequencer to provide valve operation as shown in Fig. 119. The electrical interface requirements are as previously listed in Table 8.



NOMENCLATURES

Q_o, Q_f	OXIDIZER AND FUEL VOLUMETRIC FLOWRATES
Q'_o, Q'_f	VOLUMETRIC FLOWRATE MEASUREMENT SIGNALS
P_o, P_f	FLOWMETER INLET PRESSURES
P_o', P_f'	PRESSURE MEASUREMENT SIGNALS
T_o, T_f	FLOWMETER INLET TEMPERATURES
T_o', T_f'	TEMPERATURE MEASUREMENT SIGNALS
$\dot{w}_o, \dot{w}_f$	GENERATED VALUES OF OXIDIZER AND FUEL WEIGHT FLOWRATES
MR_{REF}	COMMANDED VALUE OF OXIDIZER/FUEL WEIGHT FLOWRATE MIXTURE RATIO
ϵ_{MR}	MIXTURE RATIO ERROR
θ_{1C}	INJECTOR OXIDIZER BALL VALVE COMMANDED ANGULAR POSITION SIGNAL
θ_1	INJECTOR OXIDIZER BALL VALVE ANGULAR POSITION
P_c	COMBUSTION CHAMBER PRESSURE
P_{REF}	COMMANDED VALVE OF CHAMBER PRESSURE
ϵ_P	CHAMBER PRESSURE ERROR
θ_{2C}	PREBURNER OXIDIZER BALL VALVE COMMANDED ANGULAR POSITION SIGNAL
θ_2	PREBURNER OXIDIZER BALL VALVE ANGULAR POSITION
I_1, I_2	VALVE MOTOR ACTUATOR ELECTRIC CURRENTS
E_1, E_2	VALVE POSITION POTENTIOMETER EXCITATION VOLTAGES
θ_1', θ_2'	VALVE POSITION SIGNALS

Figure 118. PBA Controller Input-Output Diagram

TABLE 10. AUTOMATIC CUTOFF BY COMPARATOR CIRCUIT (REDLINES)

REDLINE IDENTIFICATION	AUTOMATIC MONITOR LIMIT	
LOW TURBOPUMP		
Turbopump LOX Inlet Temperature (max), K (R)	97.7	(176)
Turbopump LOX Inlet Pressure (min), kPa (psia)	634	(92)
Turbopump Speed (max), Hz (rpm)	1283	(77,000)
*Balance Piston Return Flow Temperature (max), R (K)	Δ = 5.5	(10)
*Rear Bearing Drain Temperature (max), K (R)	Δ = 5.5	(10)
*Balance Piston Cavity Pressure	TBD	
*Primary LOX Seal Drain Line Pressure (max), kPa (psig)	207	(30)
*Turbine Secondary Seal Drain Line Pressure (max), kPa (psig)	207	(30)
Intermediate Seal Purge (Helium) Pressure (max), kPa (psig)	275	(40)
*Bently Transducers (2), max, mm (inch)	0.25	(0.010)
*Turbopump Radial Accelerometer (max), g-rms	10	
*Turbopump Axial Accelerometer (max), g-rms	10	
**Turbine Radial Accelerometer (max), g-rms	10	
FUEL TURBOPUMP		
Turbine Inlet Temperature (No. 2), max, K (R)	1083	(1950)
Turbopump LH_2 Inlet Temperature (No. 1), max, K (R)	24.4	(44)
*Turbopump LH_2 Inlet Pressure (No. 2), min, kPa (psig)	586	(85)
*Pump Bearing Coolant Temperature (maximum rise after stabilization(, K (R)	Δ = 14	(25)
*Turbine Bearing Coolant Temperature	Δ = 14	(25)
*Turbopump Speed (max), Hz (rpm)	1616.6	(97,000)
Bently Transducers (2) (Observer Only), max deflection, mm (inch)	0.254	(0.010)
*Pump Tri-Axial Accelerometers (3)** (max), 9-rms	15	
Pump Balance Piston Cavity Pressure (Observer Only)	TBD	
COMBUSTION DEVICES		
Spark (min), volts	0.99	
Preburner Ignition Detect (2 of 3 thermocouples), min, K (F)	616	(650)
Chamber Ignition Detect (2 of 3 thermocouples), min, K (F)	616	(650)
Preburner Chamber Pressure (max), kPa (psig)	24 614	(3570)
Main Chamber Pressure (high), max, kPa (psig)	15 168	(2200)
Main Chamber Pressure (low), min, kPa (psig)	12 410	(1800)

NOTE: *Parameters which also require visual redline observers
**One accelerometer (radial) monitored on Vibration Safety Cutoff system.

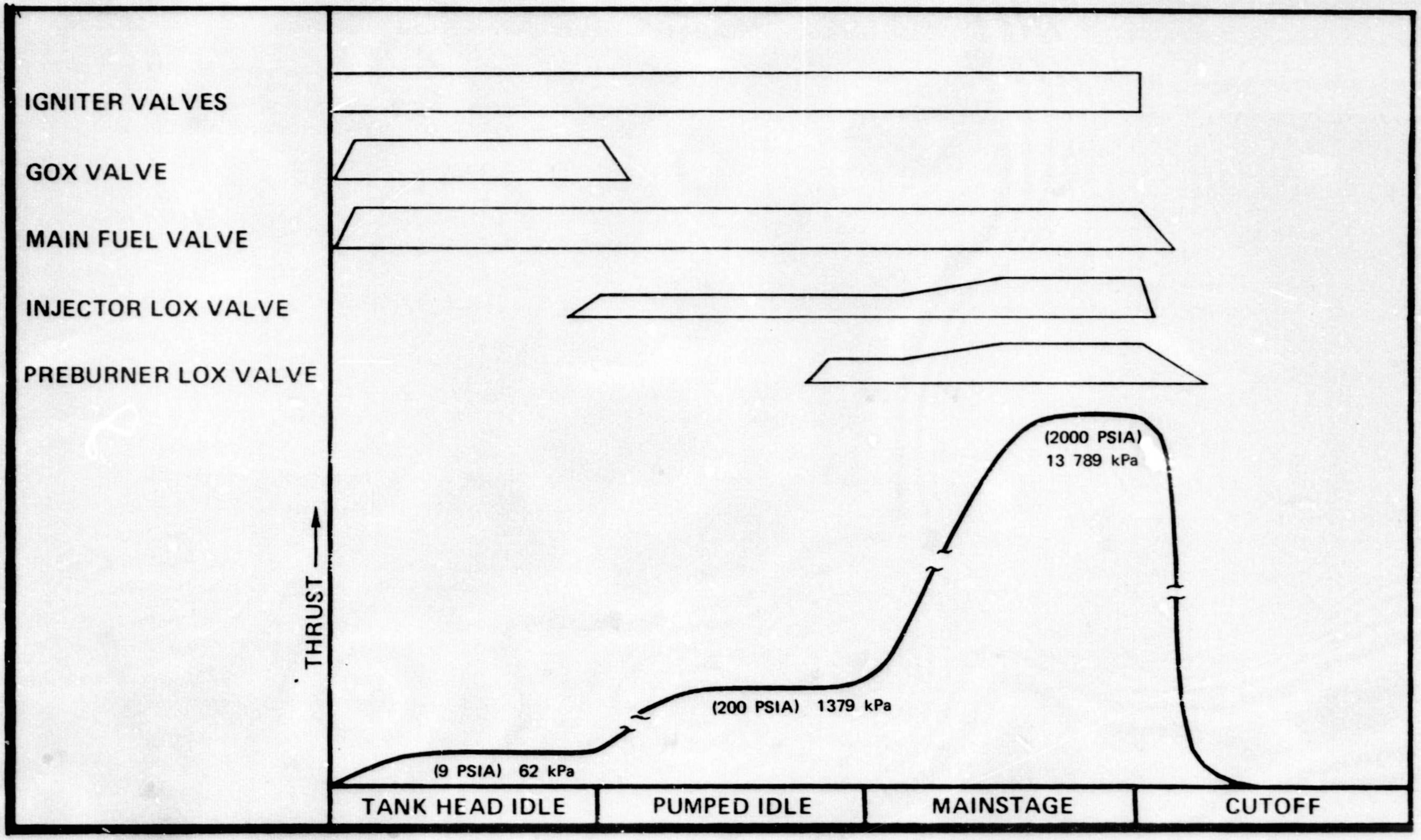


Figure 119. Breadboard Engine Start and Cutoff

PBA SYSTEM CONFIGURATION

The layout of the assembled components is presented in Fig. 120. As a result of this study, design modifications were made to the baseline (Fig. [illegible] and include the following:

1. A flat-plate two-fluid heat exchanger, 215.9 mm (8-1/2 inches) by 609 mm (24 inches) long located in the nozzle coolant outlet line, has replaced the cylindrical three-fluid exchanger located in the oxidizer turbopump turbine inlet.

2. Electric actuators have been added to valves for the main injector LOX, preburner LOX, and main fuel.

3. The space reserved for the boost pumps has been phantom-outlined.

4. The oxidizer turbopump has been moved aft to correct the turbine discharge location.

5. The nozzle coolant outlet flow has been routed through the heat exchanger and into the preburner.

6. The preburner has been rotated to accommodate the nozzle outlet line.

7. The main fuel valve has been added and the lines to it re-routed.

8. The turbopump inlets have been rotated to better accommodate the boost pumps.

9. The igniter valves have been added.

10. The fuel shunt valve and GOX valve have been added.

The design layout of the heat exchanger is presented in Fig. 121. The lines for stress analysis are identified in Fig. 122 and stress analysis details for each individual line are presented in Fig. 123 through 130.

STRUCTURAL ANALYSIS

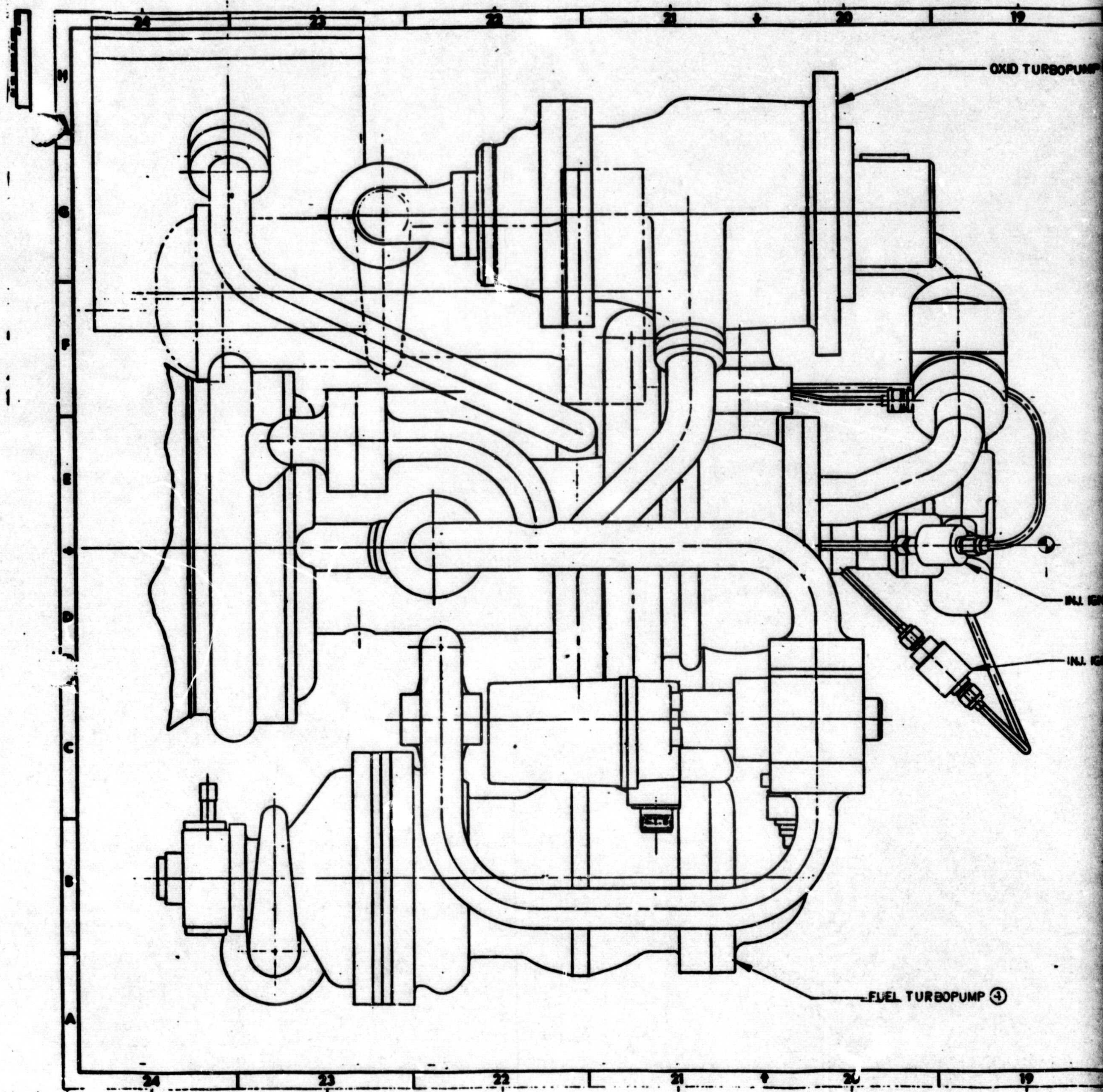
A preliminary structural analysis has been performed on the powerhead breadboard assembly lines and heat exchanger to show workability of the proposed configuration and design. The results of the analysis indicate that the proposed line routings and heat exchanger design are structurally feasible.

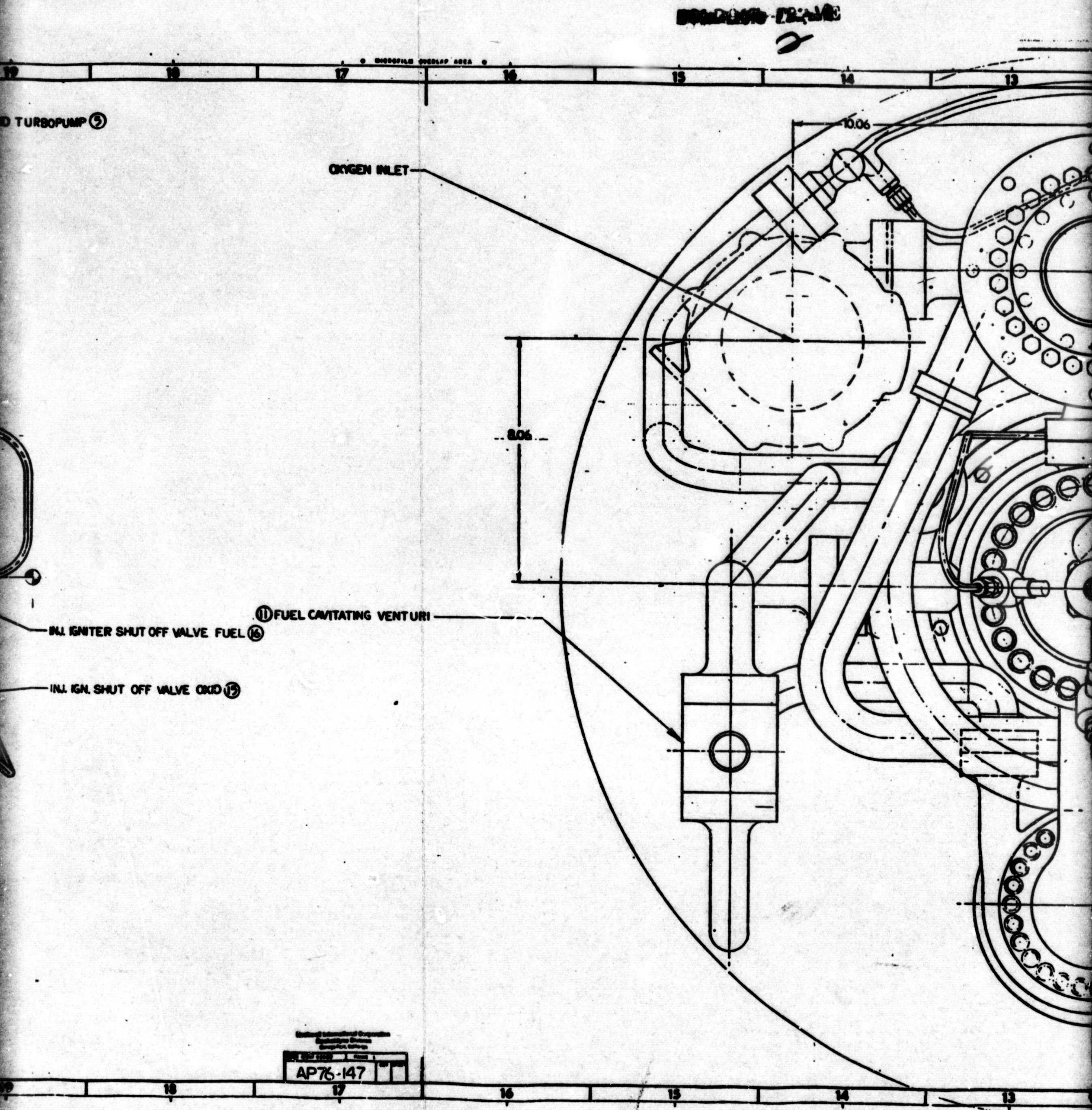
The structural criteria used for the analysis is as follows:

Factor of safety (0.2 percent yield) = 1.1 x limit load

Factor of safety (ultimate) = 1.4 x limit load

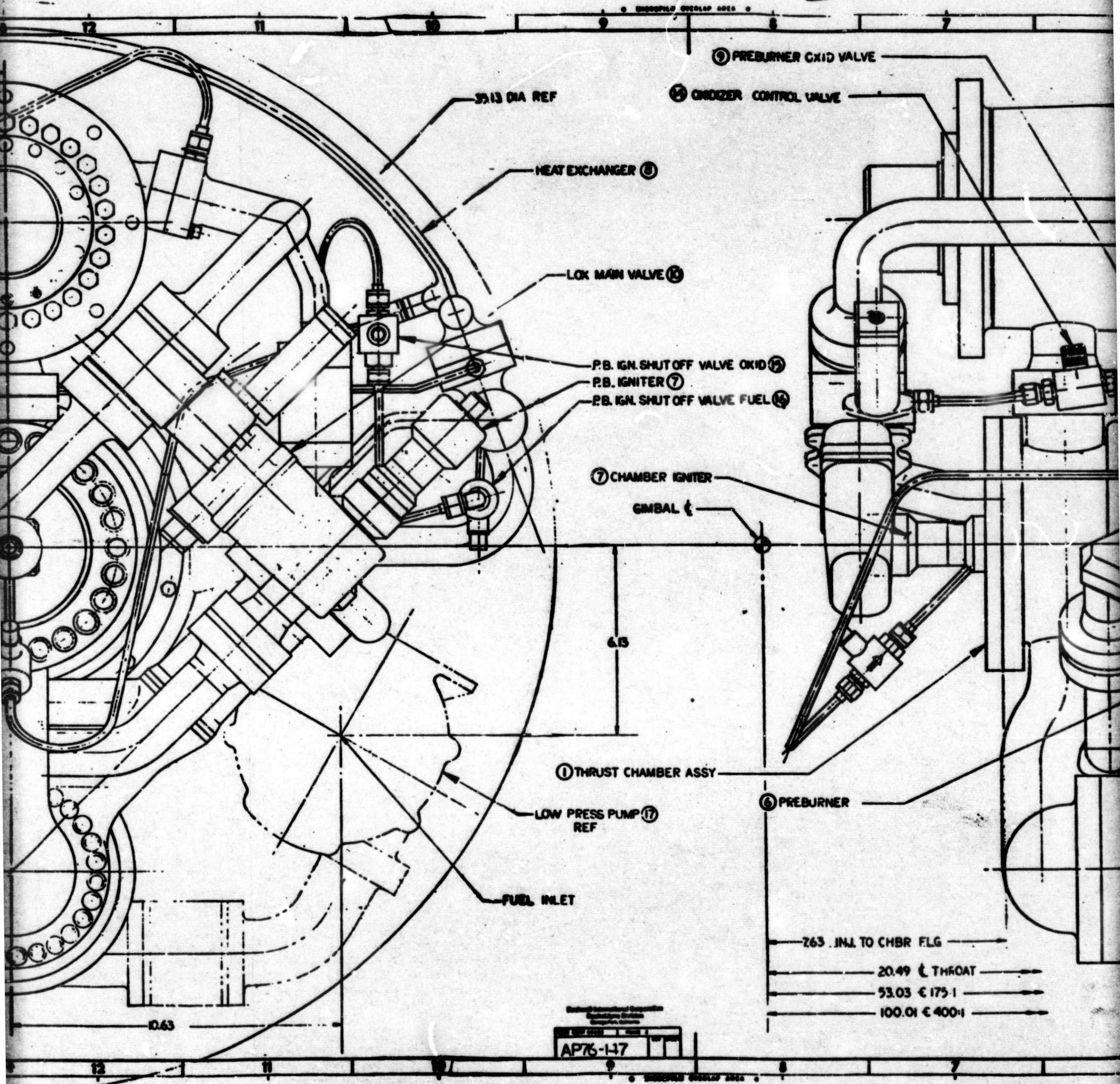
FOLDOUT FRAME 1




FOLDOUT FRAME
2
MICROFILM OVERLAP AREA
19
18
17
16
15
14
13
D TURBOPUMP ⑤
OXYGEN INLET
10.06
8.06
⑪ FUEL CAVITATING VENTURI
INJ. IGNITER SHUT OFF VALVE FUEL ⑯
INJ. IGN. SHUT OFF VALVE OXID ⑮
AP76-147

FOLDOUT FRAME

3



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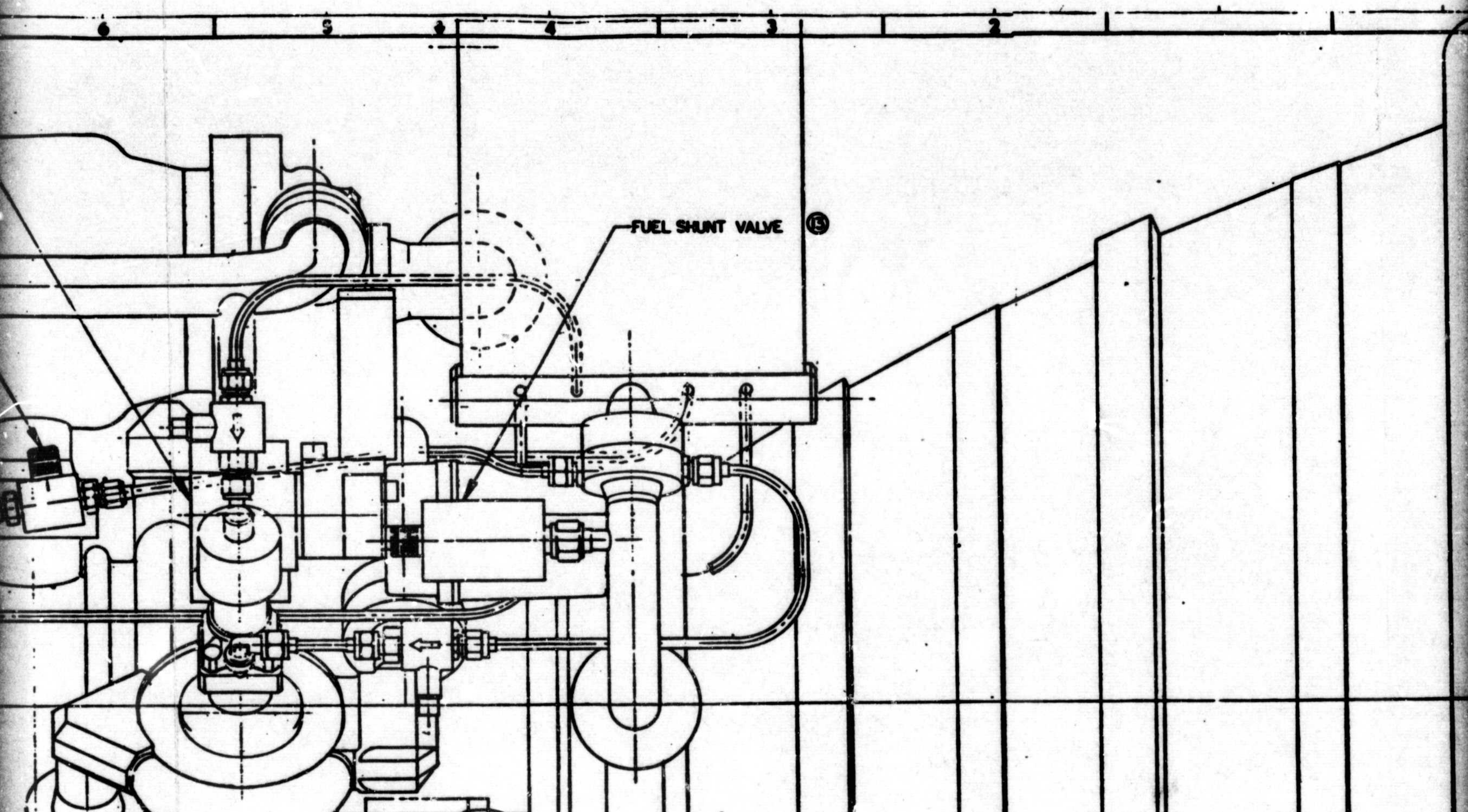

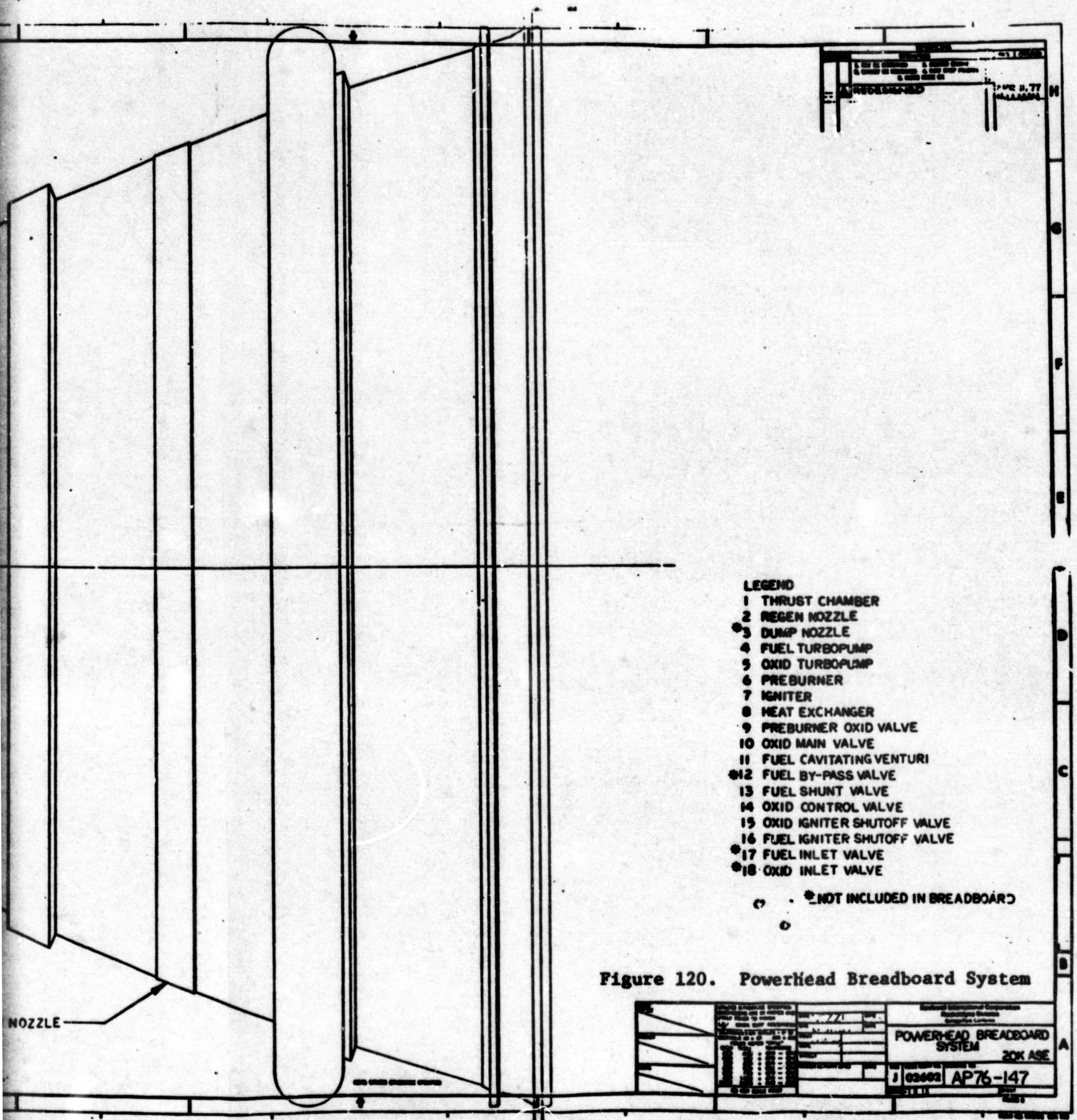

Figure 120. PowerHead Breadboard System

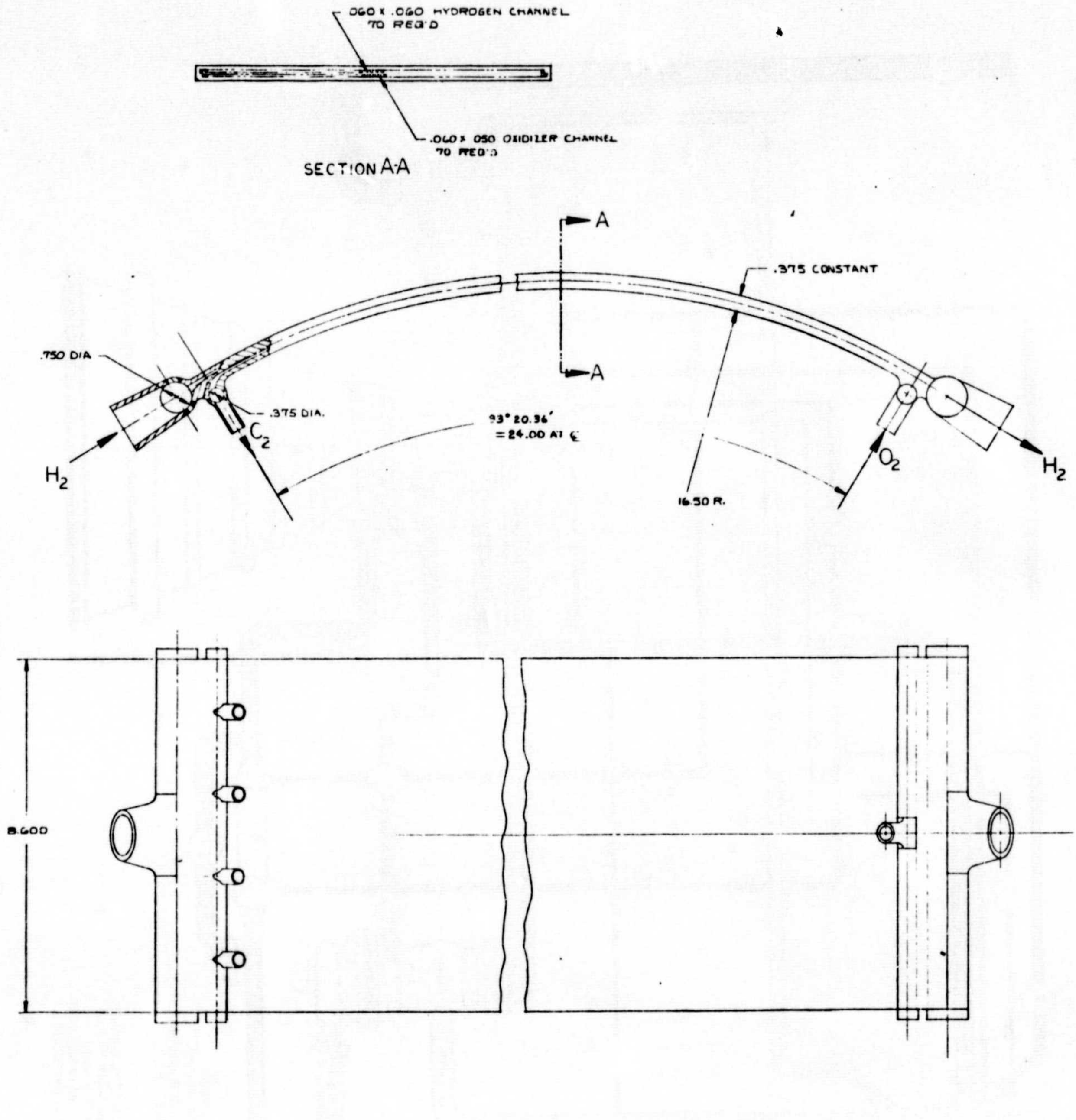

Figure 121. Heat Exchanger Design Layout

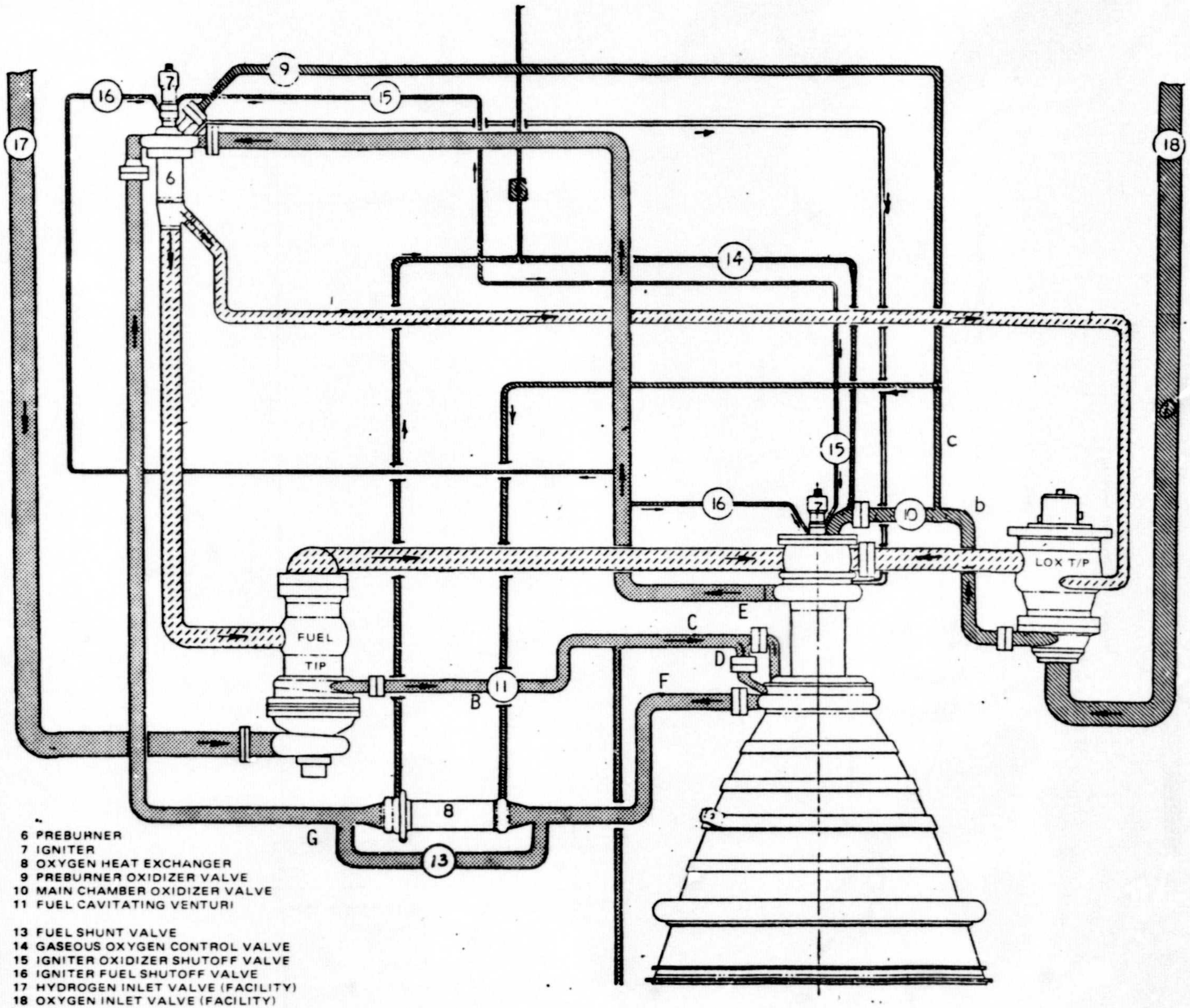

Figure 122. PBA System

MATERIAL	INCONEL 625
LINE OD, mm (IN.)	31.75 (1.75)
LINE WALL THICKNESS, mm (IN.)	3.17 (0.125
PROPELLANT	LIQUID HYDROGEN
PROPELLANT TEMPERATURE, K (R)	22 (40)
MAX WORKING PRESSURE, kPa (PSIA)	32 433 (4704)

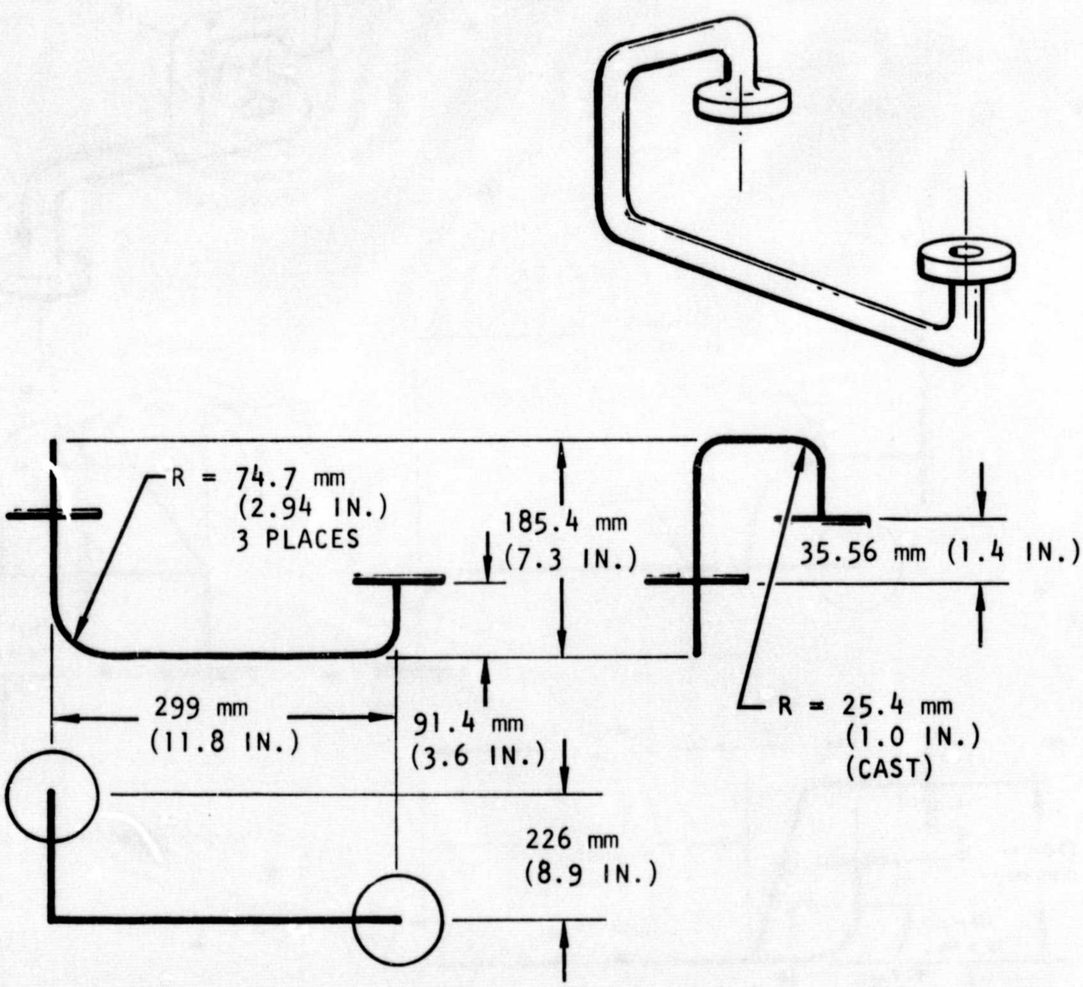

Figure 123. PBA Interconnect Line B (Fuel turbopump outlet to fuel cavitating venturi)

	LINE C		LINE D	
MATERIAL	INCONEL 625			
LINE OD, mm (IN.)	38.1	(1.50)	31.75	(1.25)
LINE WALL THICKNESS	3.17	(0.125)	3.17	(0.125)
PROPELLANT	LIQUID HYDROGEN			
PROPELLANT TEMPERATURE, K (R)	22 (40)			
MAX WORKING PRESSURE kPa (PSIA	38 433 (4704)			

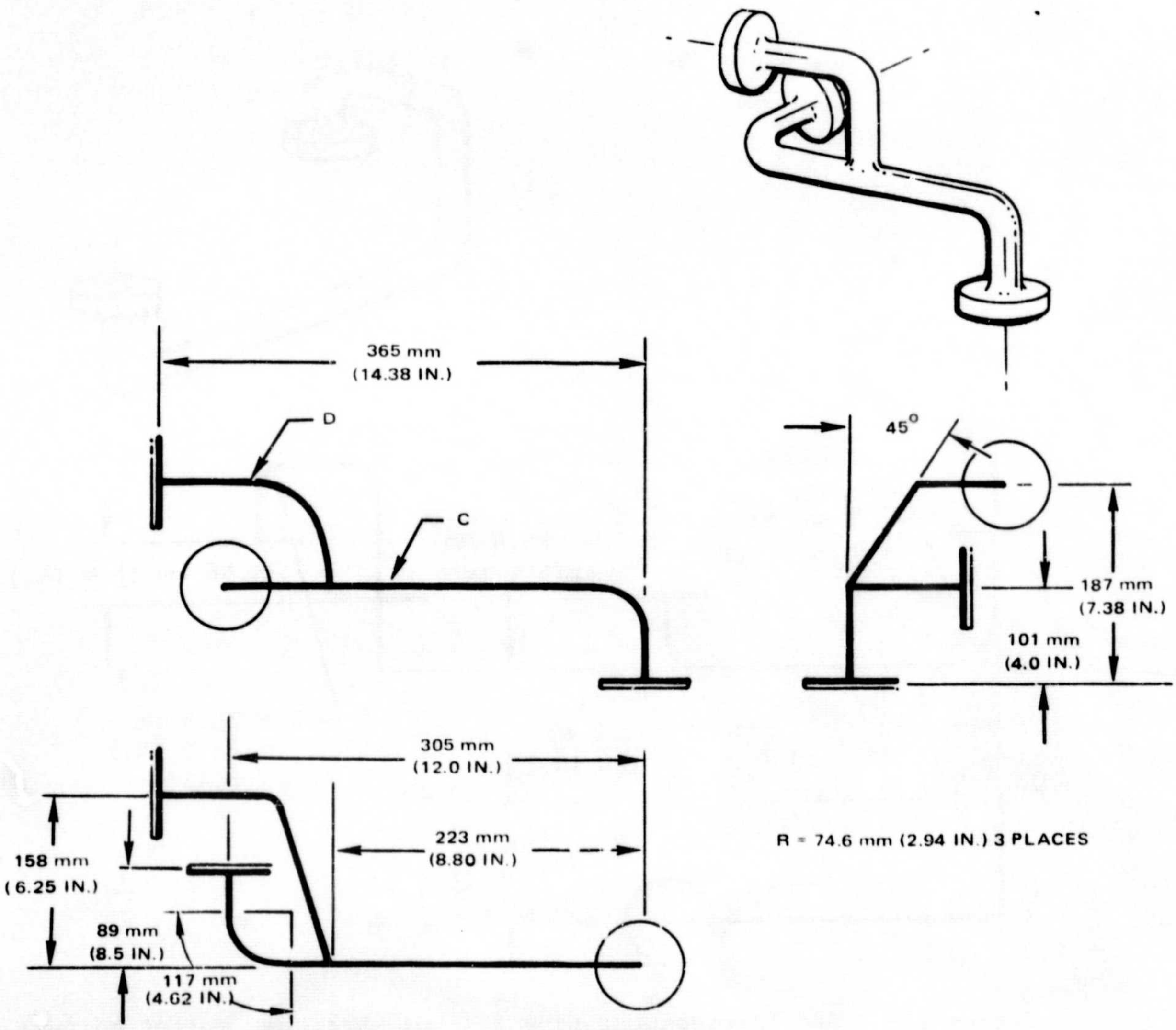

Figure 124. PBA Interconnect Line C (Fuel cavitating venturi to regen chamber) and Line D (to regen nozzle)

MATERIAL	INCONEL 625
LINE OD, mm (IN.)	38.1 (1.50)
LINE WALL THICKNESS	W.T.
PROPELLANT	HYDROGEN
PROPELLANT TEMPERATURE, K (R)	178 (322)
MAX WORKING PRESSURE, kPa (PSIA	27 310 (3961)

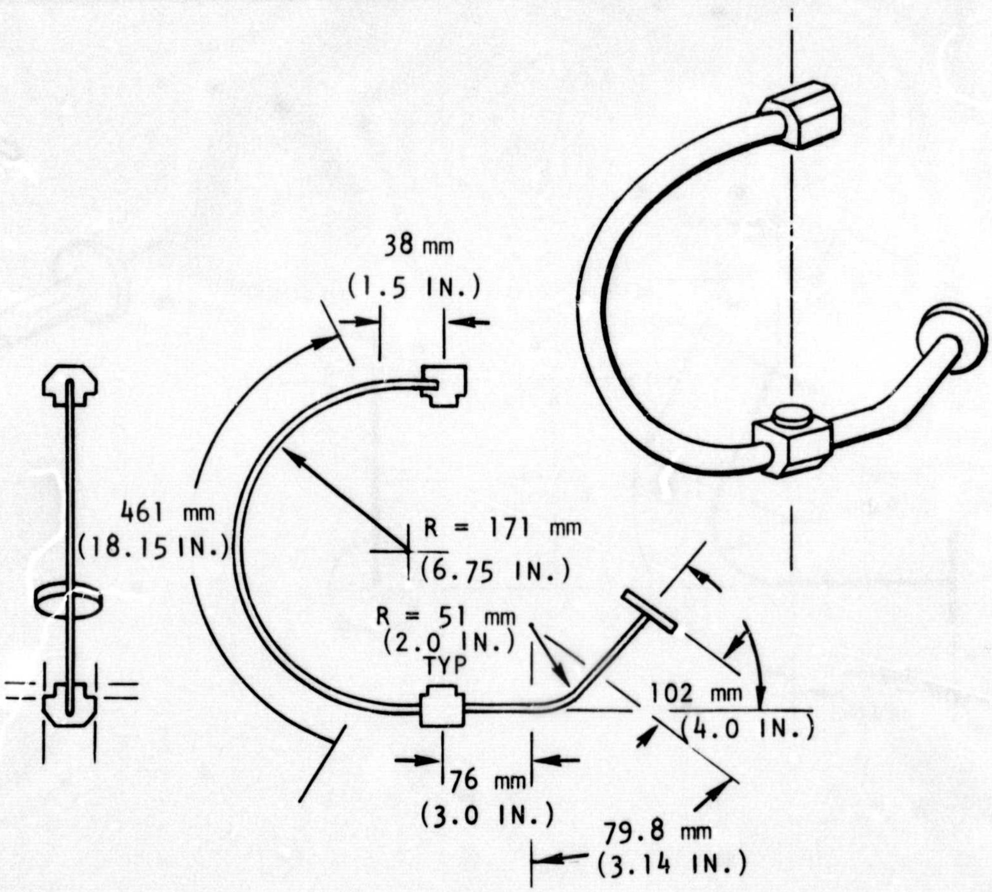

Figure 125. PBA Interconnect Line E (chamber regen exit to preburner injector)

MATERIAL	INCONEL 625
LINE OD, mm (IN.)	31.7 (1.25)
LINE WALL THICKNESS, mm (IN.)	3.17 (0.125)
PROPELLANT	HYDROGEN
PROPELLANT TEMPERATURE, K (R)	479 (863)
MAX WORKING PRESSURE, kPa (PSIA	31 943 (4633) 31943 kPa

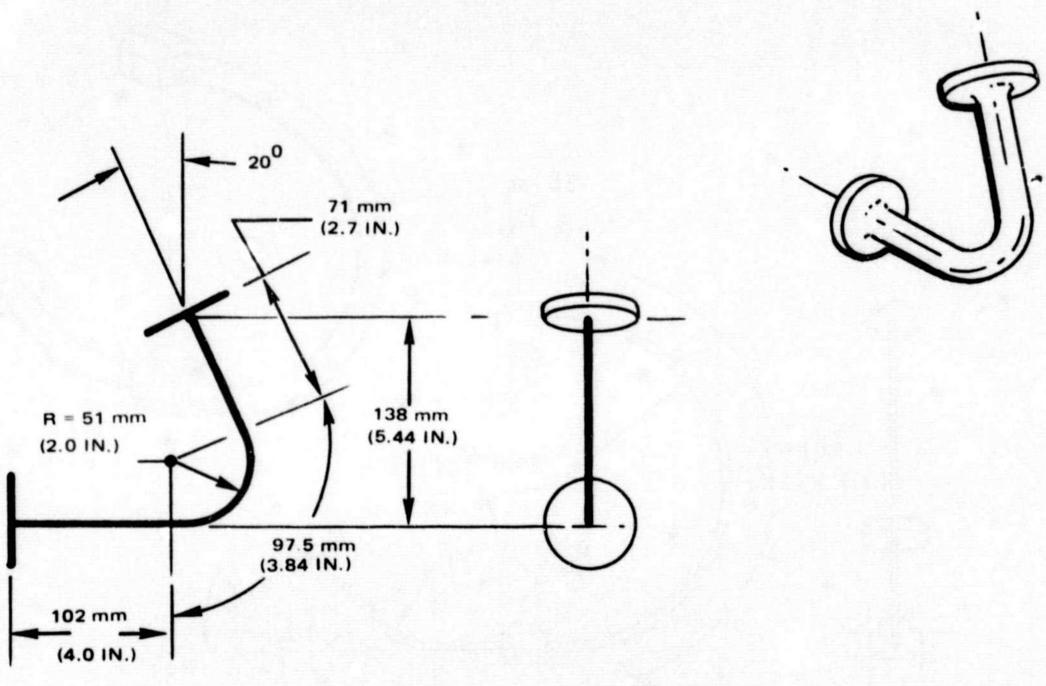

Figure 126. PBA Interconnect Line F (nozzle regen exit to heat exchanger)

MATERIAL	INCONEL 625
LINE OD, mm (IN.)	31.7 (1.250)
LINE WALL THICKNESS, mm (IN.)	3.17 (0.125)
PROPELLANT	HYDROGEN
PROPELLANT TEMPERATURE, K (R)	253 (457)
MAX WORKING PRESSURE, kPa (PSIA)	29 510 (4280)

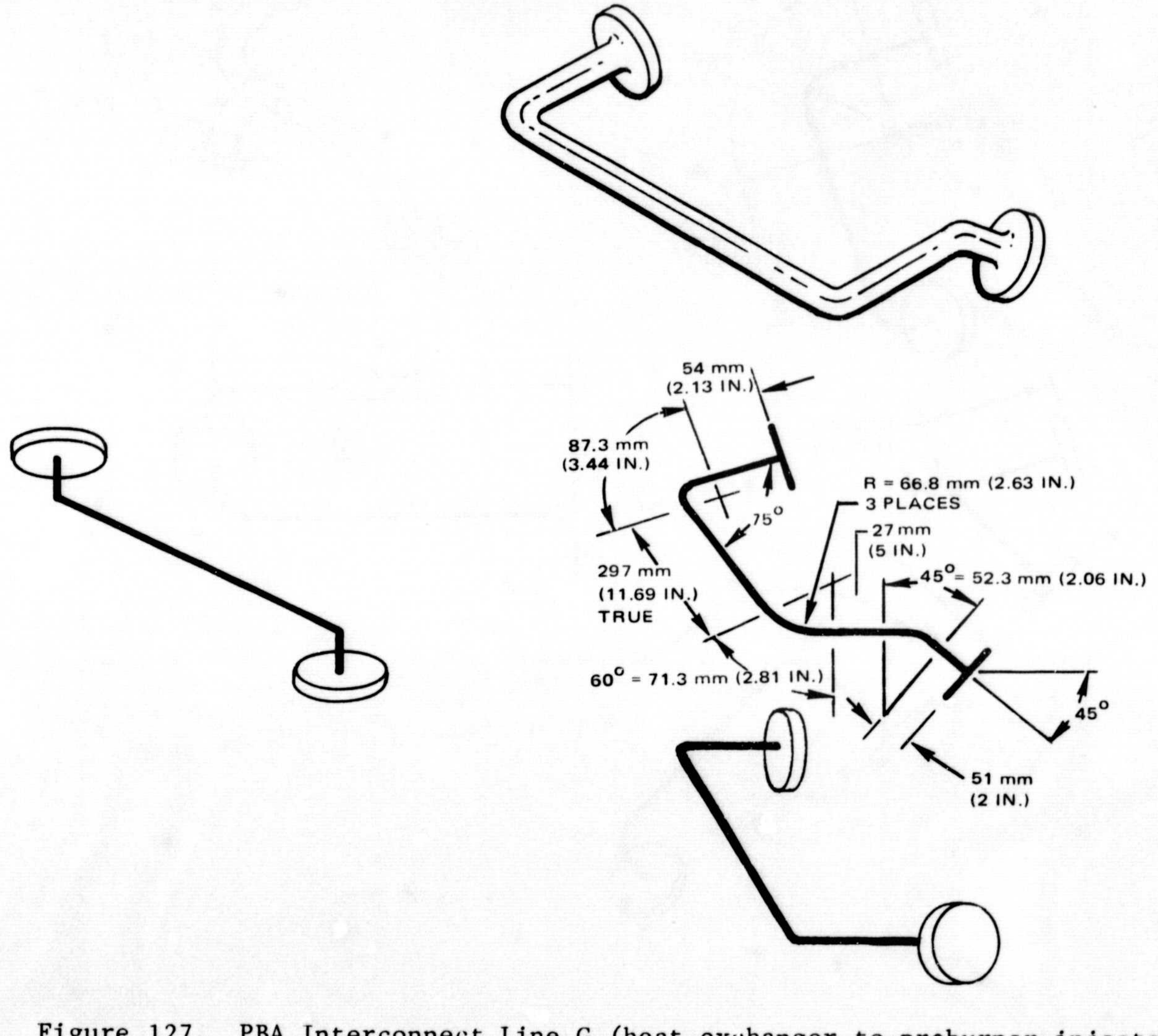

Figure 127. PBA Interconnect Line G (heat exchanger to preburner injector)

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MATERIAL	INCONEL 625
LINE OD, mm (IN.)	38.1 (1.50)
LINE WALL THICKNESS, mm (IN.)	3.17 (0.125
PROPELLANT	LOX
PROPELLANT TEMPERATURE, K (R)	108 (195)
MAX WORKING PRESSURE kPa (PSIA)	34 874 (5058)

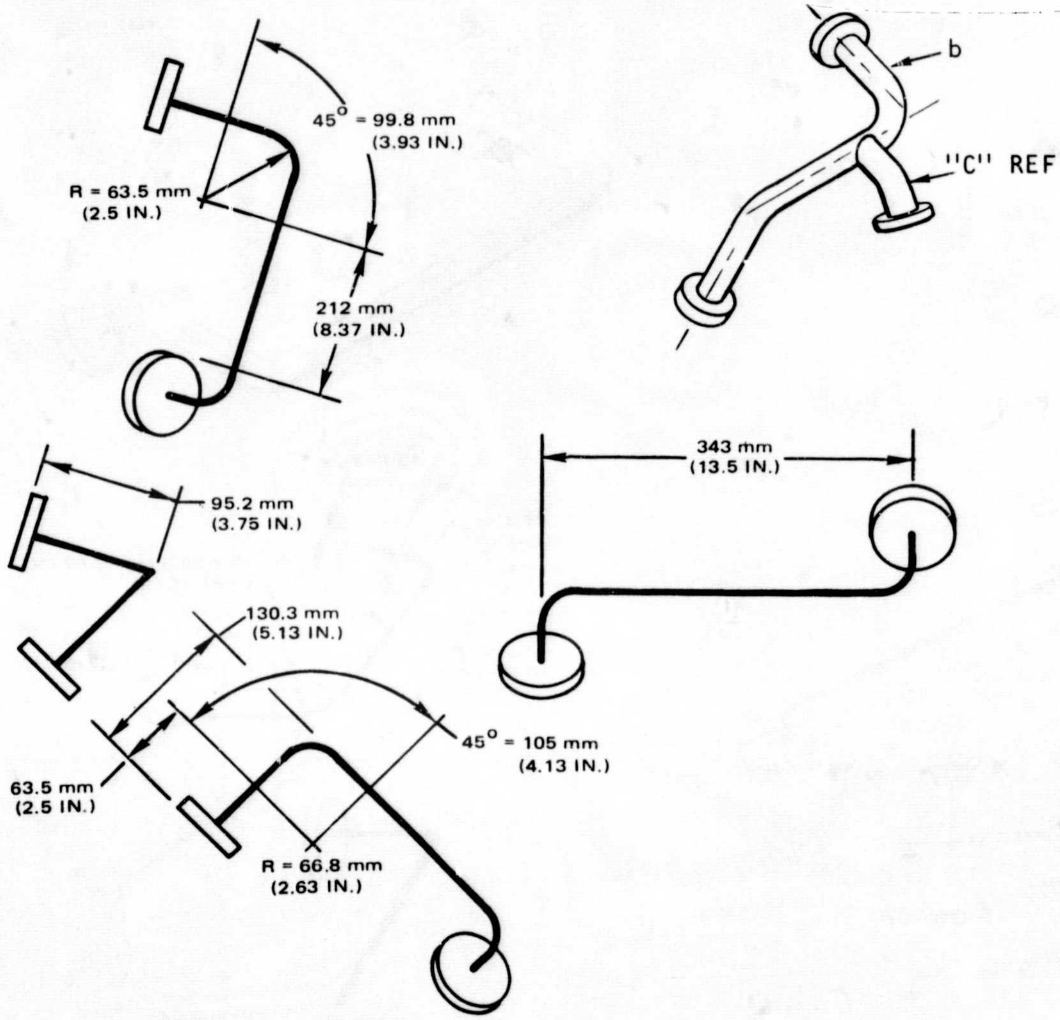

Figure 128. PBA Interconnect Line b (LOX turbopump outlet to chamber injector)

MATERIAL	INCONEL 625
LINE OD, mm (IN.)	22.35 (0.88 IN.)
LINE WALL THICKNESS, mm (IN.)	3.175 (0.125)
PROPELLANT	LOX
PROPELLANT TEMPERATURE, K (R)	108 (195)
MAX WORKING PRESSURE kPa (PSIA)	34 873 (5058)

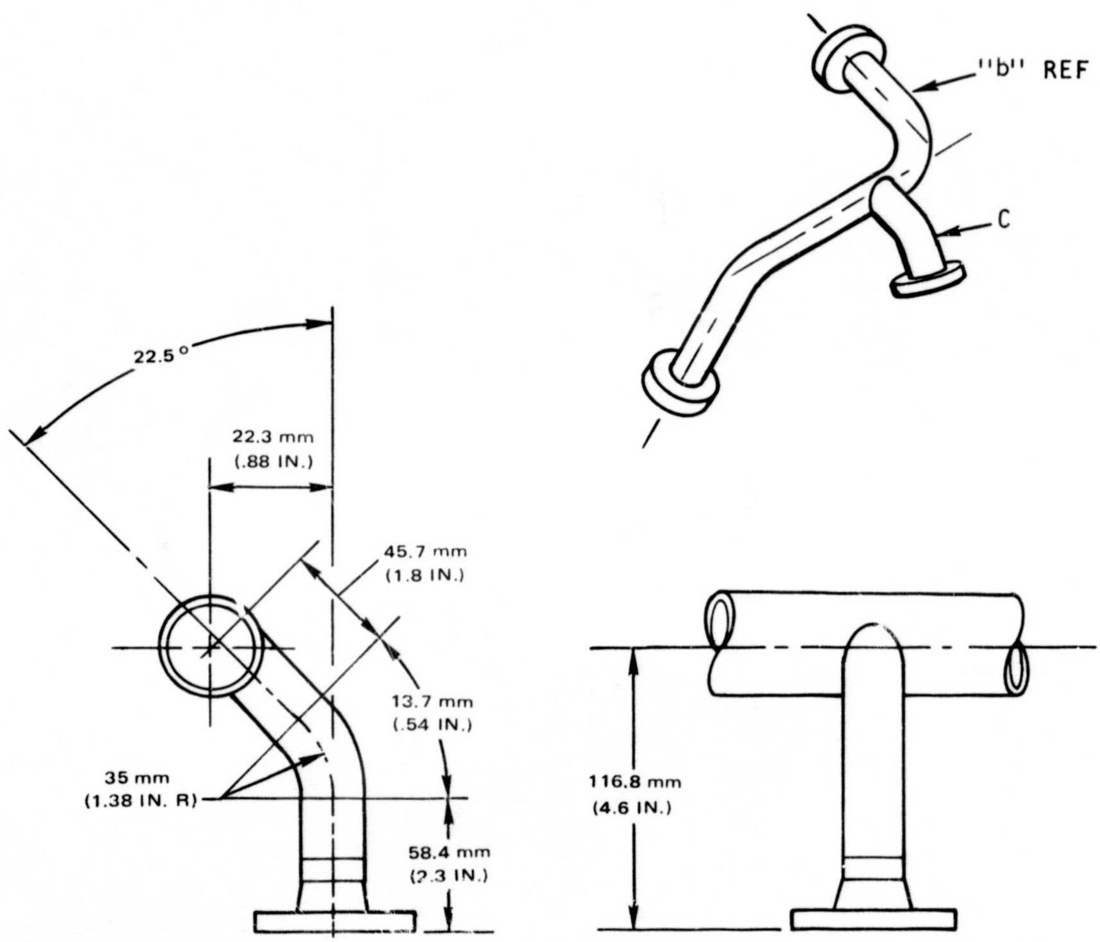

Figure 129. PBA Interconnect Line C (line b to preburner injector)

MATERIAL	INCONEL 625	
LINE OD, mm (IN.)	38.1	(1.50)
LINE WALL THICKNESS, mm (IN.)	3.17	(0.125
PROPELLANT	HYDROGEN/OXYGEN	
PROPELLANT TEMPERATURE, K (R)	944	(1700)
MAX WORKING PRESSURE kPa (PSIA)	15 706	(2278)

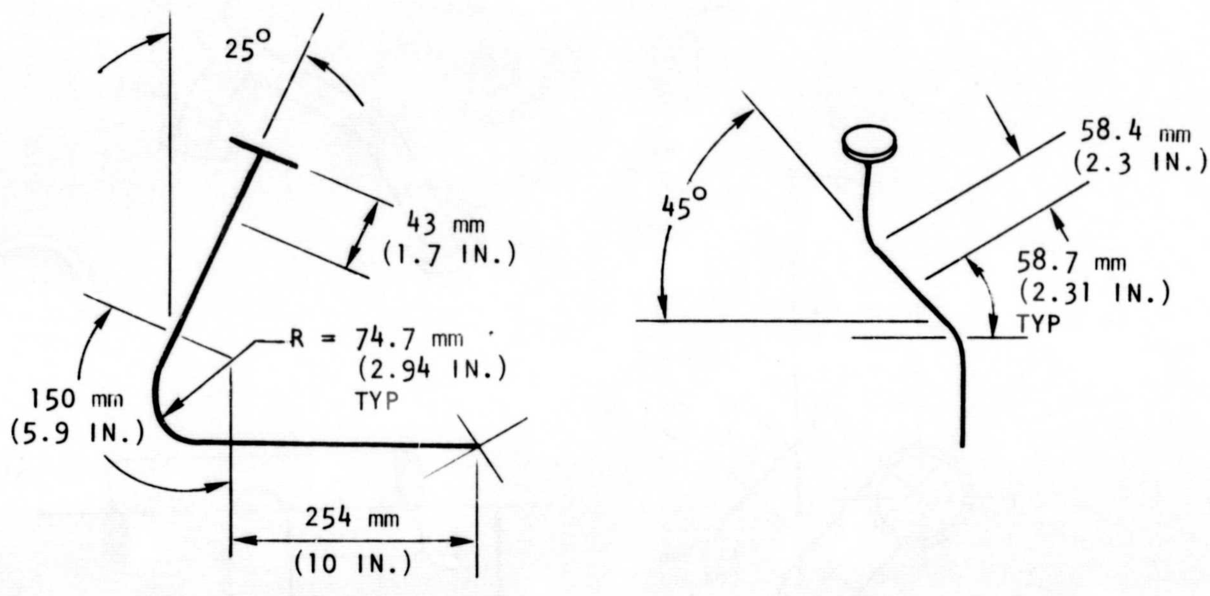

Figure 130. PBA Interconnect Line I (preburner exhaust to LOX turbopump)

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Burst pressure = 1.5 x limit pressure

Reference - NASA Zachary, A.T., Advanced Space Engine Preliminary Design, CR-121236, 1973.

The powerhead breadboard assembly lines were structurally analyzed by using the three dimensional Stardyne computer program (Fig. 131 through 133). The powerhead breadboard assembly axis system is as follows: The x axis is along the thrust chamber center line and is positive in the forward direction; the z axis is parallel to an axis passing through the fuel and oxidizer turbopumps and is positive in the direction toward the fuel turbopump; the y axis is perpendicular to the x and z axes and is positive in a direction away from the preburner. All three axes pass through the gimbal center. The major propellant and hot gas lines were modeled to interconnect and support the oxidizer and fuel turbopumps, the preburner, and the valves to the thrust chamber. The materials selected for the lines are 21Cr-6Ni-9Mn for cryogenic temperatures and Inconel 625 for elevated temperatures. One exception to this is the fuel line from the thrust chamber to the preburner which uses Inconel 625 material for welding even though it operates at 178 K (-138 F).

The lines were initially sized for internal pressure. The line loads and stresses due to operating temperature thermal deflections were then calculated separately. Also, to account for dynamic loading, an inertia force of 25 g's was applied to the lines and component weights along three perpendicular axes separately. The maximum load and stress for each line due to the above inertia force along one axis was then calculated. Each line was structurally evaluated for pressure, thermal deflection, and inertia stresses. A summary of line factors of safety for pressure and combine loading are listed in Table 11.

The hydrogen/oxygen heat exchanger was analyzed for pressures and inertia loading and found to be structurally adequate. The hydrogen components are subject to temperatures and pressures from 30 709 kPa (4454 psia) at 535 K (503 F) to 30 336 kPa (4400 psia) at 517 K (472 F). Similar data for oxygen components are from 24 131 kPa (3500 psia) at 91 K (-296 F) to 24 118 kPa (3498 psia) at 352 K (174 F). The stress of the copper/nickel panel was highest for combined load conditions of 30 709 kPa (4454 psi) pressure and 25 g inertia operating at a temperature of 518 K (474 F). Thermal strains produced by differential expansion between the NARloy A copper core and the ED Nickel shell were also considered in the analysis. The minimum yield factor of safety of 1.62 is greater than the required 1.1. The ED Nickel shell thickness was found to be more than adequate and subsequently was reduced from 2.54 mm (0.100 inch) to 1.78 mm (0.070 inch) on each side to reduce weight and improve performance.

The inlet and exit nozzles were checked for pressure and inertia loads. Since the heat exchanger is supported by the hydrogen and oxygen lines, the nozzles must react concentrated loads with bending being the primary component. The larger hydrogen inlet and exit nozzles were assumed to react all of these loads. The combined load stresses produced a yield factor of safety of 0.82 with the 3.175 mm (0.125 inch) thick 321 stainless nozzle wall. An increase in thickness

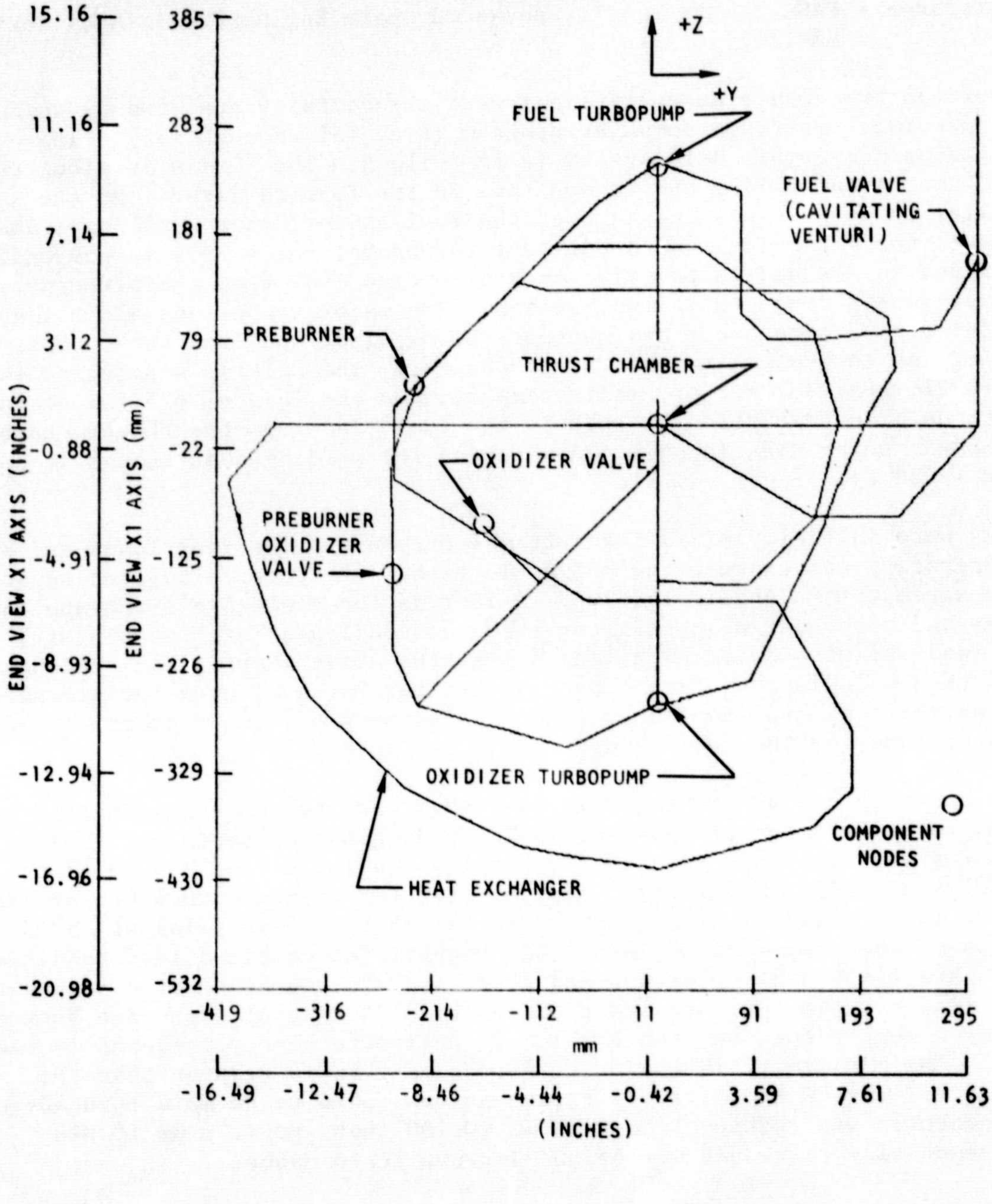

Figure 131. PBA Line Configuration (XZ plane)

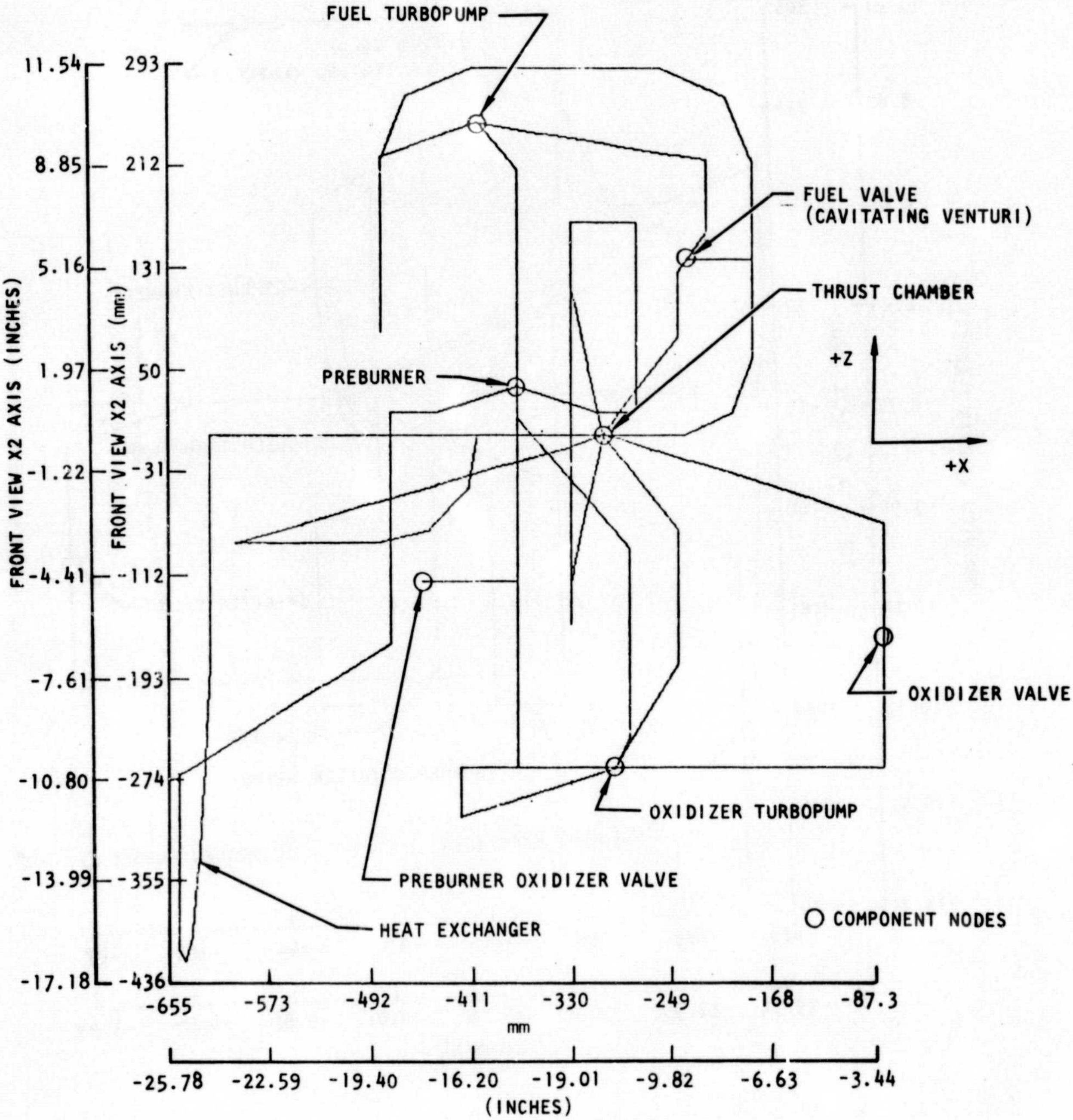

Figure 132. PBA Line Configuration (XZ plane)

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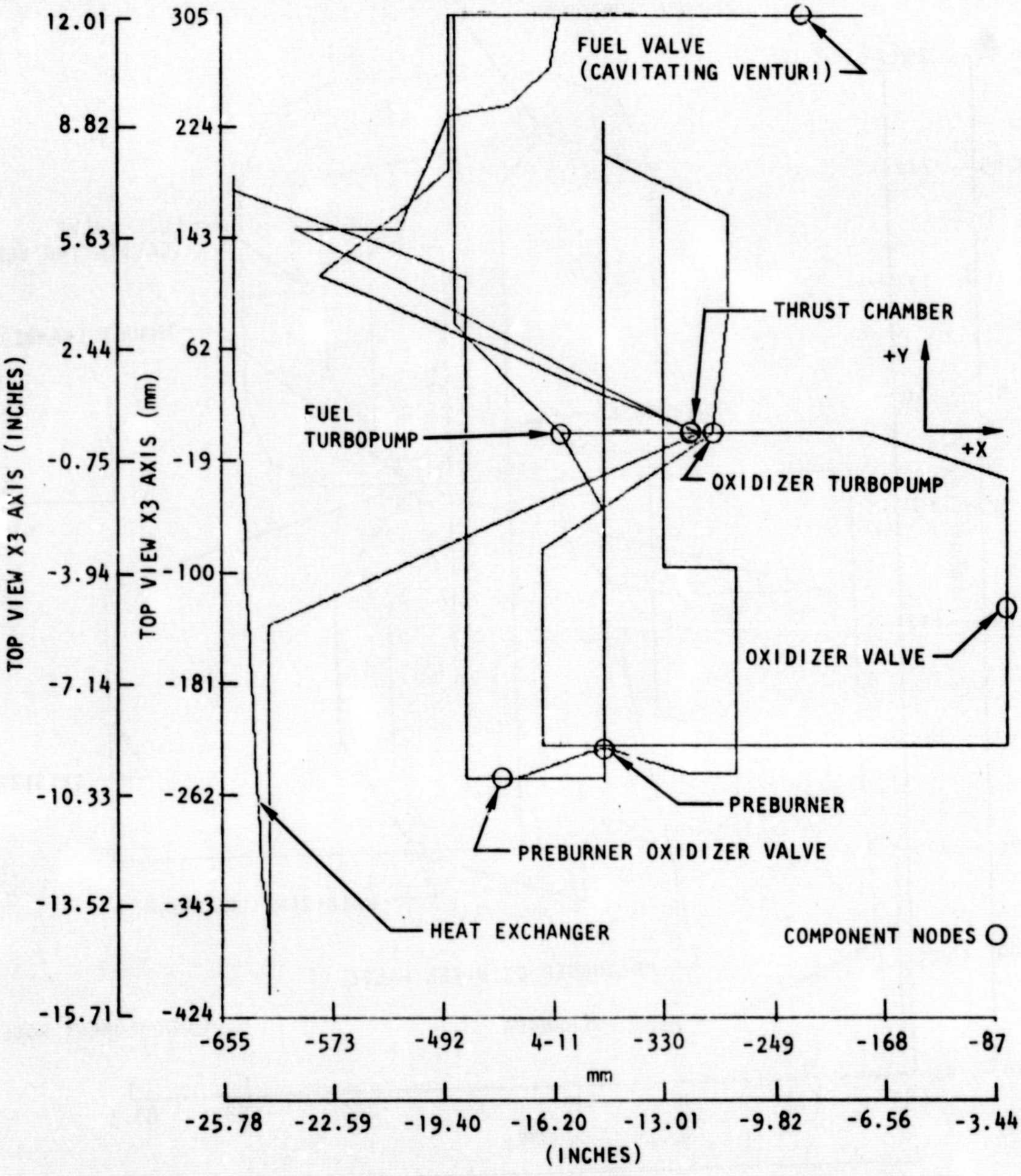


Figure 133. PBA Line Configuration (XY plane)

TABLE 11. POWERHEAD BREADBOARD ASSEMBLY LINES FACTOR OF SAFETY SUMMARY

Line Description	Limit Pressure		Temperature		Material	Line OD		Wall Thickness		Limit Pressure Safety Factor		Limit Combined Load Safety Factor	
	kPa	(psi)	K	(F)		mm	(inches)	mm	(inches)	Ultimate	Yield	Ultimate	Yield
Fuel Turbopump to Regen Nozzle	32 433	(4704)	22	(-420)	21Cr-6Ni-9Mn	31.75	(1.25)	3.175	(0.125)	8.42	5.91	6.3	4.4
Preburner to Oxidizer Turbine	23 925	(3470)	1000	(1340)	Inconel 625	38.1	(1.5)	3.175	(0.125)	3.12	1.60	3.05	1.57
Fuel Turbine to Thrust Chamber	15 720	(2280)	944	(1240)	Inconel 625	63.5	(2.5)	6.35	(0.25)	7.02	3.16	2.6	1.17
Oxidizer Turbine to Thrust Chamber	15 720	(2280)	944	(1240)	Inconel 625	57.1	(2.25)	6.35	(0.25)	7.80	3.51	2.85	1.28
Thrust Chamber to Preburner	27 310	(3961)	179	(-138)	Inconel 625	63.5	(2.5)	6.35	(0.25)	6.41	3.18	2.47	1.23
Oxidizer Turbopump to Thrust Chamber	34 874	(5058)	108	(-265)	21Cr-6Ni-9Mn	38.1	(1.5)	3.175	(0.125)	2.48	1.61	2.30	1.49
Oxidizer Line to Preburner	34 874	(5058)	108	(-265)	21Cr-6Ni-9Mn	38.1	(1.5)	3.175	(0.125)	2.48	1.61	2.48	1.61
Preburner to Fuel Turbine	15 720	(2280)	1000	(1340)	Inconel 625	63.5	(2.5)	8.25	(0.325)	7.95	4.09	2.95	1.52
Heat Exchanger to Preburner	29 510	(4280)	516	(470)	Inconel 625)	38.1	(1.5)	3.175	(0.125)	3.97	1.67	2.77	1.17
Regen Nozzle to Heat Exchanger	31 923	(4630)	535	(503)	Inconel 625	38.1	(1.5)	3.97	(0.1563)	4.55	1.89	2.69	1.12

to 4.77 mm (0.188 inch) will bring the factor up to an acceptable 1.22 value. The low factor could also be resolved by changing the material from stainless steel 321 to Inconel 625 which results in a 1.53 yield factor. A summary table of the lowest factors of safety are listed in Table 12.

TABLE 12. POWERHEAD BREADBOARD ASSEMBLY HEAT EXCHANGER FACTOR OF SAFETY SUMMARY

Item	Limit Pressure		Temperature		Material	Limit Pressure Safety Factor		Limit Combined Load Safety Factor	
	kPa	(psi)	K	(F)		Ultimate	Yield	Ultimate	Yield
Tube Panel Nickel Shell	30 709	(4454)	519	(474)	Electrodeposited Nickel	18.7	10.5	2.08	1.18
Copper Core	30 709	(4454)	519	(474)	NARloy A	9.2	2.64	3.14	1.62
H_2 Inlet Nozzle	30 709	(4454)	535	(503)	321 CRES at t = 3.175 mm (0.125 inch)	2.56	0.95	2.22	0.82[a]
					321 CRES at t = 4.77 mm (0.188 inch)	3.63	1.34	3.32	1.22[b]
					Inconel 625 at t = 3.175 mm (0.125 inch)	4.43	1.77	3.84	1.53[c]

[a]Can either increase thickness or change material as shown in (b) and (c).

The powerhead breadboard assembly line configuration and heat exchanger design are structurally feasible based on preliminary analysis. Additional structural analyses are required to evaluate the detail designs. It is recommended that a dynamic evaluation be performed on the lines. Also, the heat exchanger assembly should be mounted to the thrust chamber to provide a more stable support and reduce dynamic loads.

LOX HEAT EXCHANGER

REQUIREMENTS AND CANDIDATE CONFIGURATIONS

The PBA is designed to provide autogenous pressurization of vehicle propellant tanks. Gaseous fuel, for fuel tank pressurization, is readily available from the main chamber and nozzle coolant. However, to provide gaseous oxygen for oxidizer tank pressurization, a separate heat exchanger is required. This LOX heat exchanger also provides gaseous oxygen for the main chamber igniters during all modes of engine operation and to the preburner igniter during mainstage. During tank head idle, the heat exchanger also provides gaseous oxidizer to the main chamber.

The potential locations utilizing heated hydrogen and preburner gas for the LOX heat exchanger are shown in Fig. 134. A three-fluid heat exchanger would combine locations 3, 4, 5, 6, or 7 with 1 or 2. The requirements and guidelines for the heat exchanger design are shown in Table 13. The minimum required gaseous oxygen temperatures and the preliminary oxygen, preburner gas, and hydrogen flowrates are presented along with representative heat exchanger lengths at two heat exchanger locations. Heat exchanger flowrates vary as much as a factor of 116 to 1.

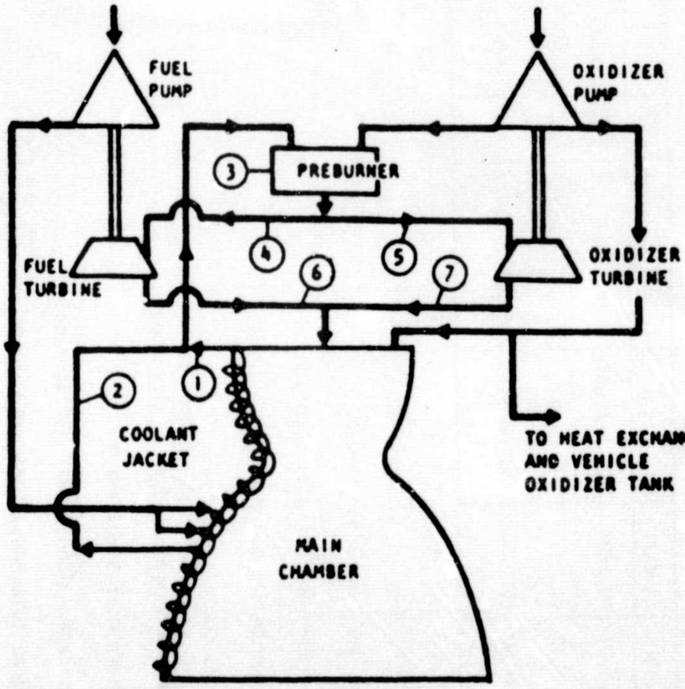


Figure 134. Potential Oxygen Heat Exchanger Locations

TABLE 13. LOX HEAT EXCHANGER REQUIREMENTS AND GUIDELINES

Engine Operational Mode	Maximum Oxygen Inlet Temperature: 95 K (172 R)															
	Preburner Gas				Cooling Circuit Combustor Discharge				Cooling Circuit Nozzle Discharge				Oxygen			
	(a) T_{gas}, IN.		(a) T_{gas}, IN.		(a) $\dot{w}$		(a) T_{H_2}, IN.		(a) $\dot{w}$		(a) T_{H_2}, IN.		(a) $\dot{w}$		(a) Minimum T_{O_2}, OUT	
	kg/s	(lb/sec)	K	(R)	kg/s	(lb/sec)	K	(R)	kg/s	(lb/sec)	K	(R)	kg/s	(lb/sec)	K	(R)
Mainstage	4.17	(9.188)	982	(1768)	2.04	(4.5)	178	(320)	0.581	(1.283)	534	(963)	0.106	(0.234)	234	(423)
Powered Idle	0.72	(1.59)	162	(293)	0.185	(0.407)	64	(115)	0.136	(0.30)	209	(377)	0.041	(0.09)	143	(258)
Tank Head Idle	0.009	(0.020)	133	(241)	0.023	(0.05)	93	(169)	0.0049	(0.011)	320	(577)	0.039	(0.086)	GAS	

(a) Preliminary Values

- Maximum Heat Exchanger Length
  - Oxidizer Turbine Inlet Location
    - Two Sections: 229 mm (9 inches)
  - Nozzle Coolant Discharge
    - Approximately 457 mm (18 inches)
- Boost Pump Heat Requirements
  - Mainstage: 7560 cal/s (30 Btu/sec)
  - Powered Idle Mode: 756 cal/s (3 Btu/sec)
  - Tank Head Idle Mode: 0

Observing the hydrogen and preburner gas temperatures at powered idle mode shown in Table 13, a three-fluid heat exchanger using the combustor coolant discharge flow (location 1) would not vaporize the oxygen flow since the hydrogen is at a lower temperature than the inlet oxygen temperature of approximately 91 K (164 Higher hydrogen temperature is available in the system at the nozzle coolant discharge (location 2). Placement of the heat exchanger in the nozzle coolant discharge line could influence the boost pump operation and, therefore, the heat required to run the boost pumps is also presented in Table 13. Since the preburner is internally dump cooled, location 3 would not provide the necessary heat source.

The split-flow coolant flow circuit for the thrust chamber provides high temperature hydrogen at the nozzle coolant discharge which should be sufficient to gasify the oxygen for the three engine operational modes. Based on these required heat values, a simple two-fluid heat exchanger could be designed in the nozzle coolant discharge location which would absorb sufficient heat from the hydrogen to vaporize the oxygen and yet have enough remaining heat to run the boost pumps. This configuration would eliminate the necessity of the hot gas flow (two-fluid heat exchanger instead of a three-fluid heat exchanger) which would greatly simplify the heat exchanger design and therefore provide a more reliable heat exchanger. Also, the operational temperature differential would be less than with a heat exchanger with hot gas which greatly reduces the thermal growth and cycle life problems.

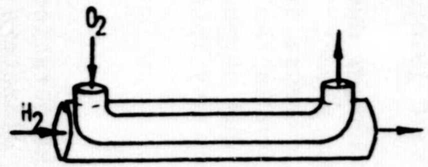
The candidate two-fluid exchangers are shown in Fig. 135 along with their features and possible problem areas. The simplest of these conditions is the concentric tube approach where the oxygen flows in the center tube and the hydrogen in the annulus. Due to its relatively large hydraulic diameter, this configuration will be typically long. The coiled tube within a tube is a modification of the concentric tube approach to reduce the heat exchanger length. With a continuous inner tube, both turbular concepts do not contain a inter-propellant joint.

The panel heat exchanger configuration enables a shorter heat exchanger due to its small hydraulic diameters. Also, since channels form the flow passages, the channel depth may be changed along the panel length to minimize pressure drop. The fourth configuration is merely the milled channel configuration in the form of a cylinder. In both of the panel configuration, the hydrogen and oxygen channels could be machined from one piece of material which eliminates any interpropellant joint.

CONCENTRIC TUBE CONFIGURATION

The results of the analysis performed for the concentric tube configuration are presented in Fig. 136 and 137. For different oxidizer tube inside diameters (different oxygen mass velocities), the heat exchanger length required to deliver the required temperatures shown in Table 13 were determined. As shown in Fig. 136, mainstage and tank head idle modes dictated the heat exchanger length. The small diameters (higher oxygen mass velocity) resulted in shorter lengths. At these small diameters, the tank head idle mode governed the heat exchanger length. Also, it is this engine operational mode for which the oxygen pressure drop is

CANDIDATE TWO-FLUID HEAT EXCHANGERS

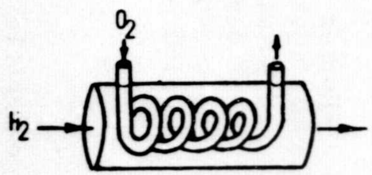


FEATURES

- SIMPLE CONCEPT
- LOW COST
- LOW ΔPS

POSSIBLE PROBLEMS

- LONG HEAT EXCHANGER

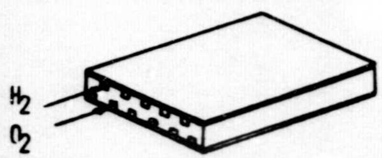


FEATURES

- SIMPLE CONCEPT
- SHORTER HEAT EXCHANGER

POSSIBLE PROBLEMS

- GEOMETRIC COMPATIBILITY

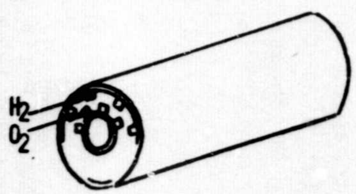


FEATURES

- SHORT HEAT EXCHANGER
- SIMPLE CONCEPT
- VARIABLE O_2H_2 FLOW AREA

POSSIBLE PROBLEMS

- FABRICATION COST
- O_2H_2 SEALING



FEATURES

- SHORT HEAT EXCHANGER
- SIMPLE CONCEPT
- VARIABLE O_2H_2 FLOW AREA

POSSIBLE PROBLEMS

- FABRICATION COST
- O_2H_2 SEALING

Figure 135. Candidate Two-Fluid Heat Exchangers

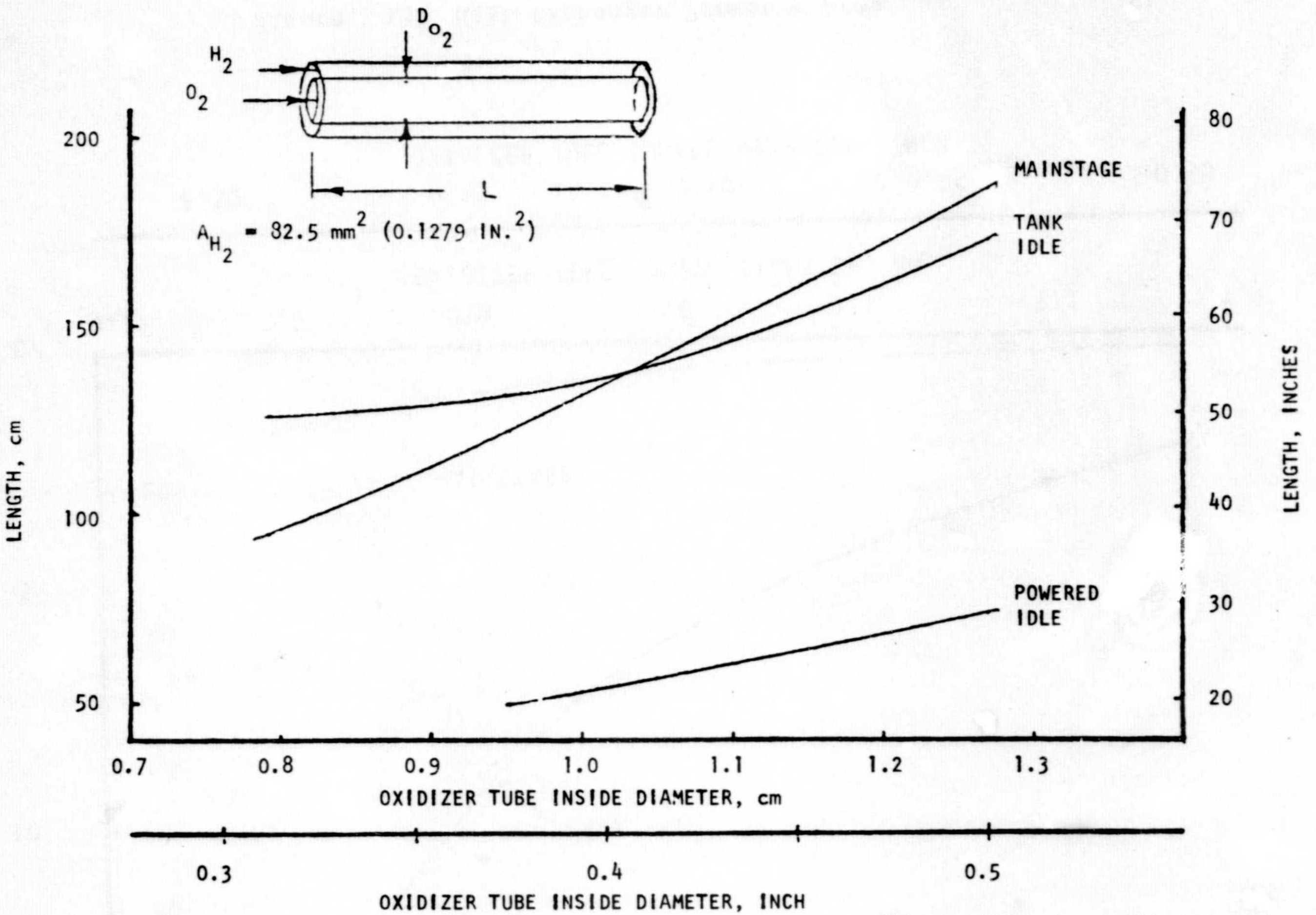


Figure 136. Heat Exchanger Operation at Different Modes

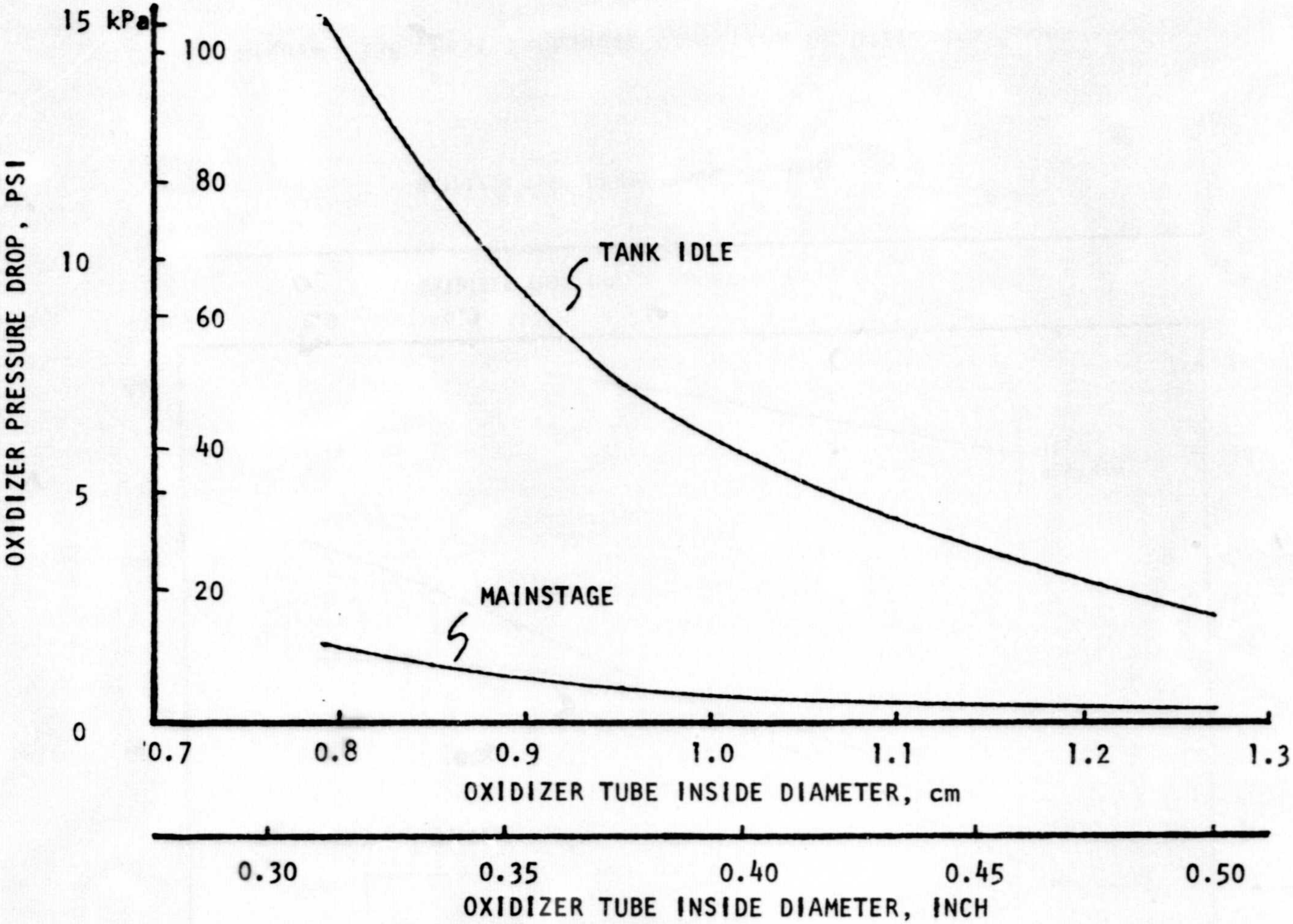


Figure 137. Heat Exchanger Pressure Drop

the most critical as shown in Fig. 137, since the inlet to the heat exchanger is only approximately 103 kPa (15 psia). Therefore, for a concentric tube heat exchanger with a 34 kPa (5 psi), oxygen pressure drop at tank head idle would be approximately 1448 mm (57 inches) which is too long to enable efficient packaging.

PANEL CONFIGURATION

Parametric data for the panel heat exchanger configuration were generated for tank head idle mode with variations in oxygen mass velocity, heat exchanger length, and heat exchanger width for a single-pass hydrogen and oxygen concept. Both constant and variable depth channel designs were evaluated.

The parametric results at the most critical heat exchanger operational mode (tank head idle mode) are shown in Fig. 138 through 140. To provide an efficient heat exchanger, high thermal conductivity materials such as copper or NARloy should be used. The following analysis was performed assuming copper. Sufficient heat is absorbed from the gaseous hydrogen to vaporize the oxygen (Fig. 138); however, a confortable margin in heat absorbed would be desirable. In an attempt to increase this margin, high oxygen mass velocities, longer lengths, widths, and variable channel depths were evaluated. The heat input margin could be increased to approach 2 percent (Fig. 138) by using a variable channel depth geometry, longer lengths, wider widths, and higher oxygen mass velocities. However, as shown in Fig. 139, this increase in heat input results in high oxygen pressure drcps and high oxygen exit Mach numbers. This is more readily apparent in Fig. 140. Therefore, to limit the oxygen pressure drop at the tank head idle mode to less than 618 kPa (1 psi) results in a 0.6 percent heat input margin. However, this will be somewhat alleviated by the heat absorbed by the oxygen as it travels to the heat exchanger from the pump and propellant lines. A saturated liquid oxygen heat exchanger inlet condition was assumed for the analysis. Therefore, a baseline heat exchanger configuration which resulted in a low oxygen pressure drop 3.4 kPa (0.5 psi), at tank head idle mode and a 0.6 percent heat input margin was selected as follows:

Dimensions, mm (inches)	457 (18) by 216 (8.5)
Oxygen Channels	
Number	70
Width, mm (inch)	1.27 (0.050)
Depth, mm (inch)	1.524 (0.060)
Hydrogen Channels	
Number	70
Width, mm (inch)	1.524 (0.06)
Depth, mm (inch)	1.524 (0.06)

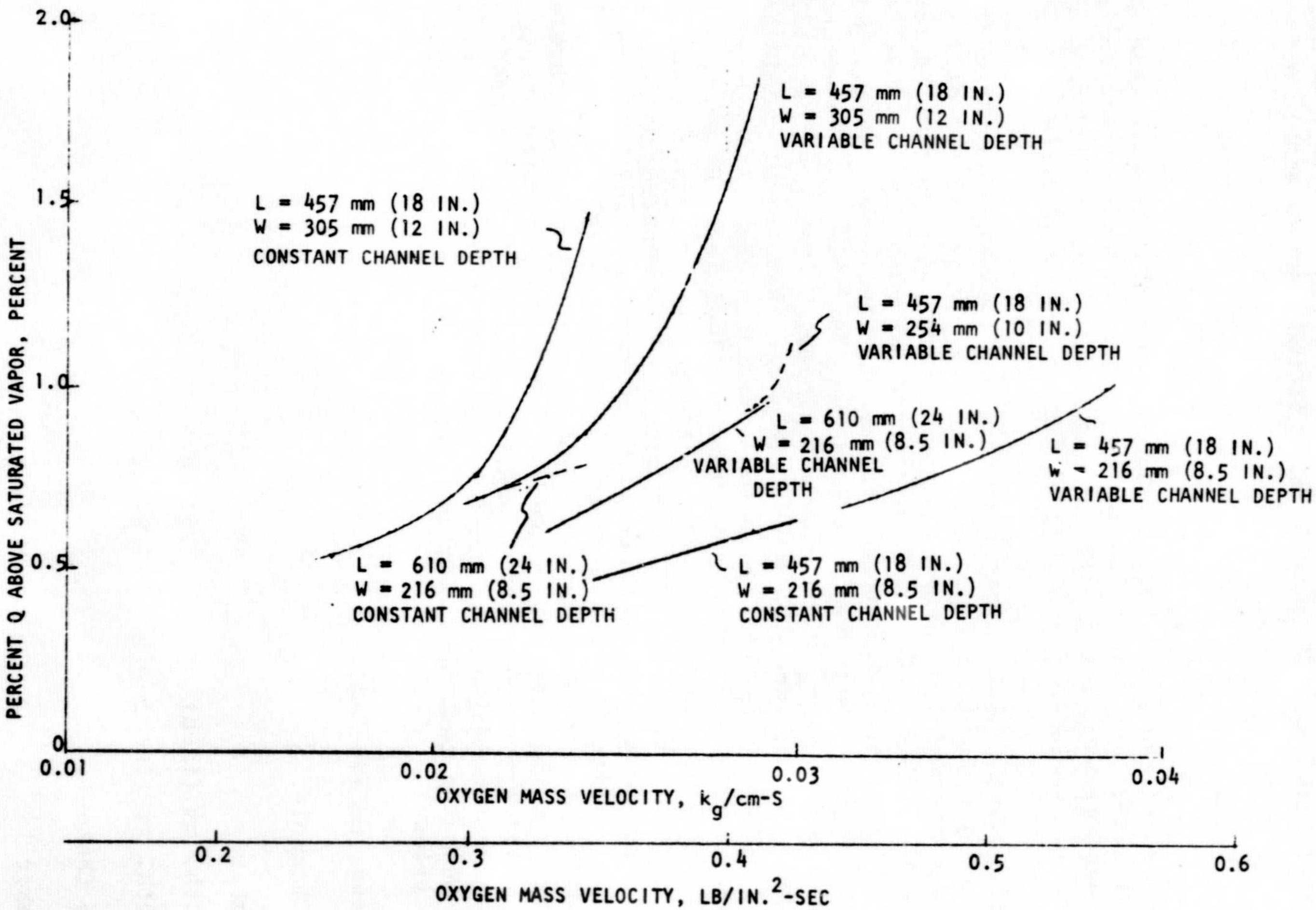


Figure 138. Different Heat Exchanger Configurations

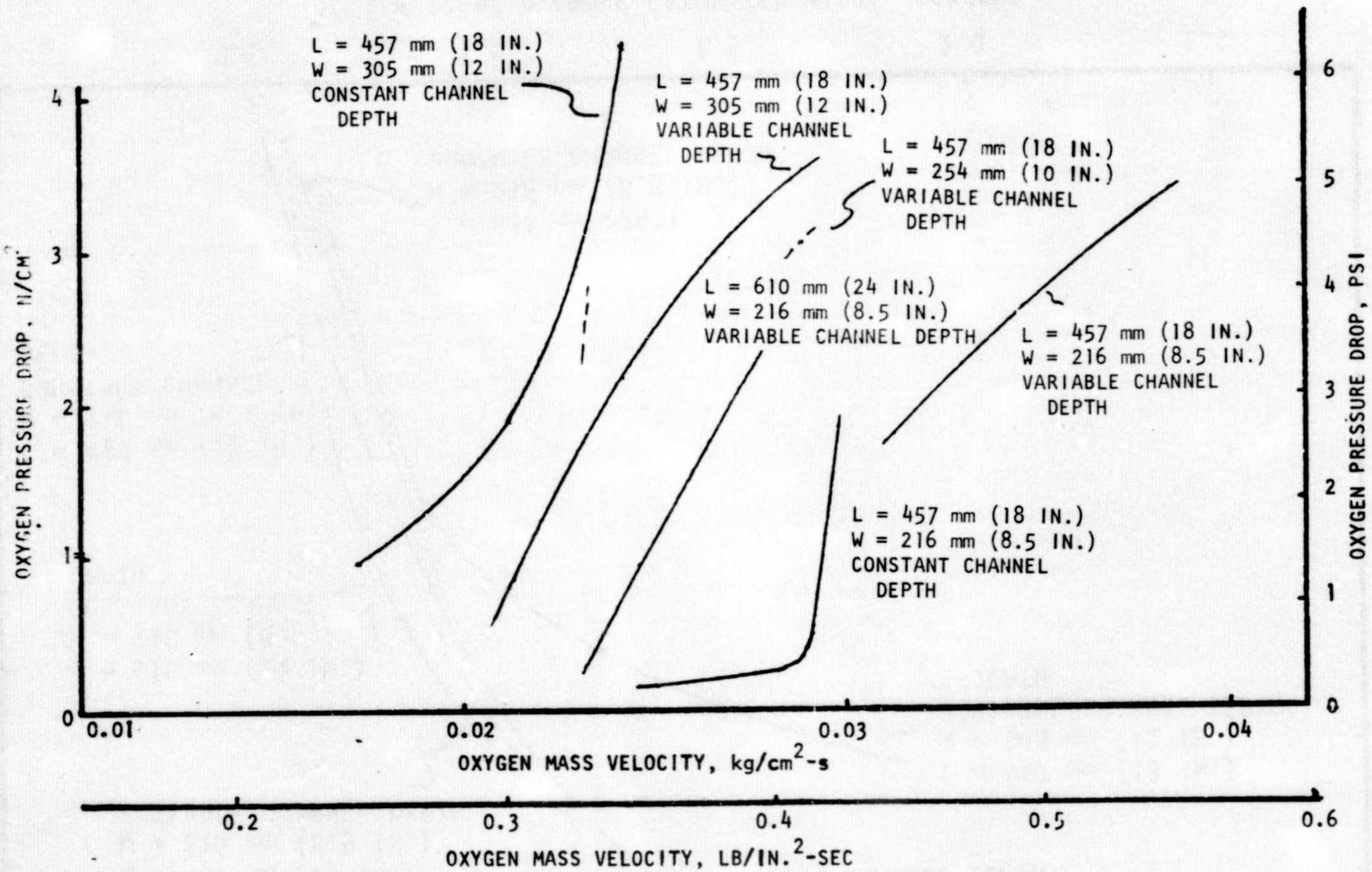


Figure 139. Heat Exchanger Pressure Drop

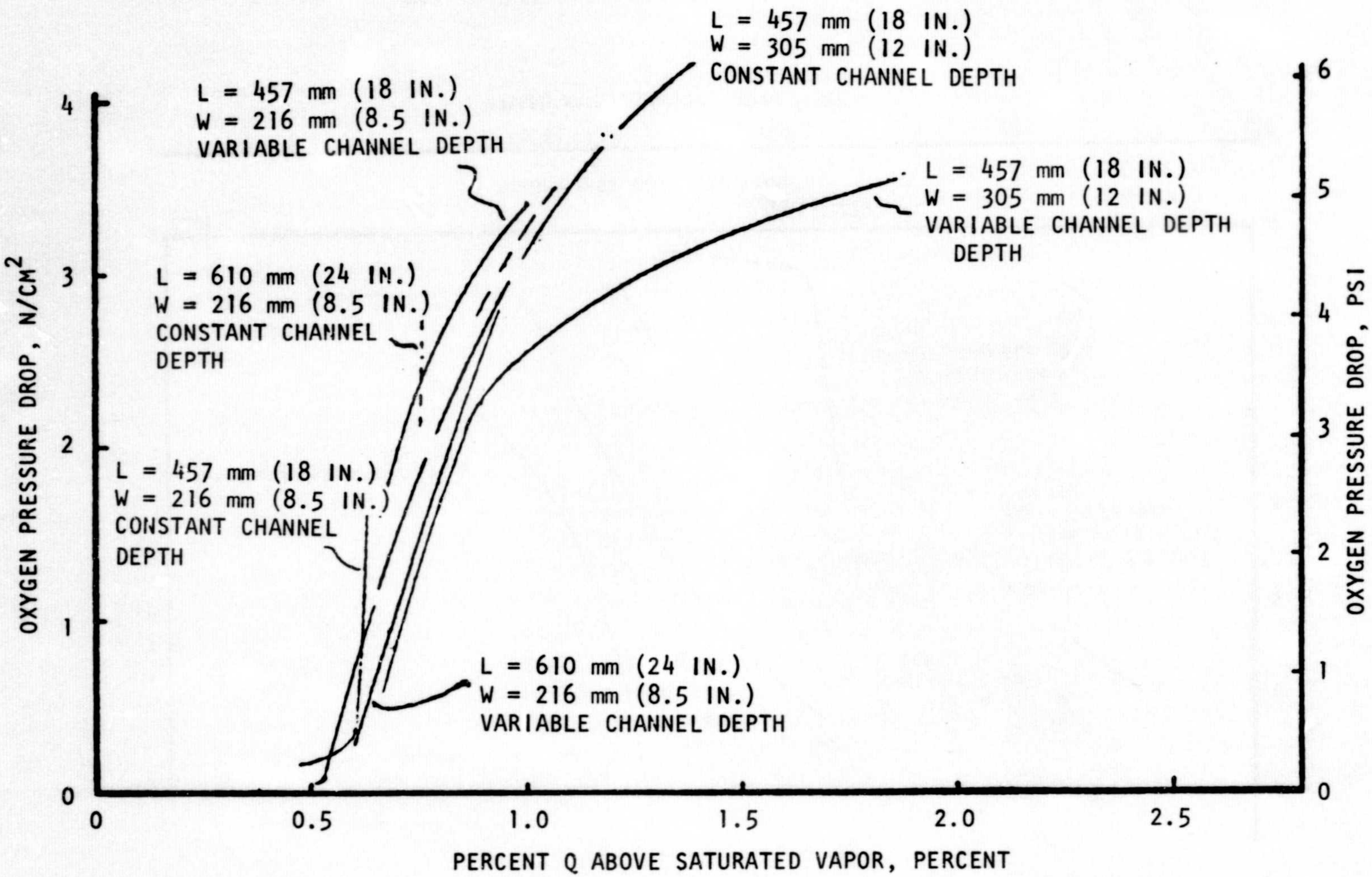


Figure 140. Heat Exchanger Operation for Diferent Configurations

This heat exchanger design was analyzed for powered idle and mainstage engine operational modes using nominal hydrogen flows. As shown in Table 14, the hydrogen pressure exceeded 551 kPa (80 psi) at powered idle and 3447 kPa (500 psi) at mainstage conditions. Since the oxygen outlet temperatures at these conditions far exceeded the minimum required, the hydrogen flow through the heat exchanger at these conditions could be reduced using a fuel shunt valve. As shown in Fig. 141 and 142, this significantly reduced the hydrogen pressure drop without a significant sacrifice in the oxygen outlet temperature. As shown in Fig. 142 and Table 15, a flow of 75 percent of nominal at powered idle and 30 percent of nominal at mainstage reduces the hydrogen pressure drop to less than 345 kPa (50 psi).

TABLE 14. PRELIMINARY HEAT EXCHANGER TEMPERATURE PERFORMANCE

ASSUMED LOX HEAT EXCHANGER CONFIGURATION

L = 457 mm (18 inches)

W = 216 mm (8.5 inch)

02: 70 Channels
1.27 mm x 1.52 mm
(0.05 x 0.06 inch)

H_2: 70 Channels
1.52 mm x 1.52 mm
(0.06 x 0.06 inch)

Operational Mode	T_{H_2}, IN		T_{H_2}, OUT		ΔP_{H_2}		T_{O_2}, IN		T_{O_2}, OUT		ΔP_{O_2}	
	R	(R)	K	(R)	kPa	(psi)	K	(R)	K	(R)	kPa	(psi)
Tank Head Idle	320	(577)	207	~(373)	26.4	~(3.83)	90.3	(162.7)	91.6	(165.1)	3.65	(0.53)
Powered Idle	210	(377)	204	~(367)	565	~(82)	91	(164)	194	(349.3)	1.86	(0.27)
Mainstage	534	(963)	529	~(954)	3537	~(513)	91	(164)	355	(640.2)	7.92	(1.15)

TABLE 15. FINAL HEAT EXCHANGER TEMPERATURE PERFORMANCE

ASSUMED HEAT EXCHANGER CONFIGURATION

L = 457 mm (18 inches)

O_2: 70 Channels
1.27 x 1.52 mm
(0.05 x 0.06 inch)

H_2: 70 Channels
1.52 x 1.52 mm
(0.060 x 0.06 inch)

Engine Operational Mode	Hydrogen								Oxygen							
	$\dot{w}_{H_2}$		T_{H_2}, IN		T_{H_2}, OUT		ΔP_{H_2}		$\dot{w}$		T_{O_2}, IN		T_{O_2}, OUT		ΔP_{O_2}	
	kg/s	(lb/sec)	K	(R)	K	(R)	kPa	(psi)	kg/s	(lb/sec)	K	(R)	K	(R)	kPa	(psi)
Tank Head Idle	0.005	(0.011)	320	(577)	207	~(373)	26.4	~(3.83)	0.039	(0.086)	90.3	(162.7)	91.6	(165.1)	3.65	(0.53)
Powered Idle	0.102	(0.225)	210	(377)	202	~(365)	317	~(46)	0.041	(0.09)	91	(164)	192	(346.7)	1.83	(0.266)
Mainstage	0.175	(0.385)	534	(963)	517	~(932)	317	~(46)	0.106	(0.234)	91	(164)	352	(633.6)	7.784	(1.129)

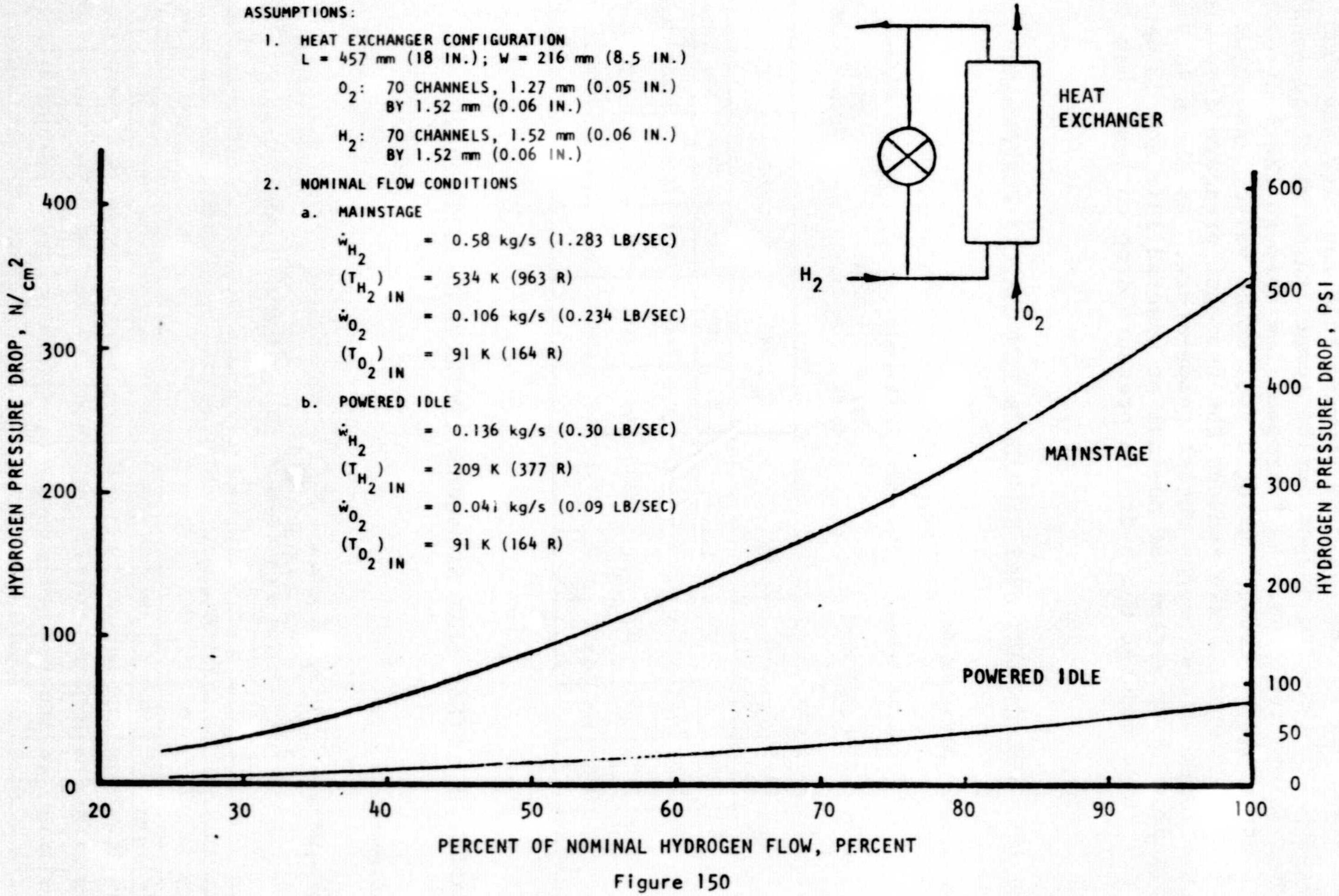


Figure 141. Heat Exchanger Hydrogen Pressure Drop

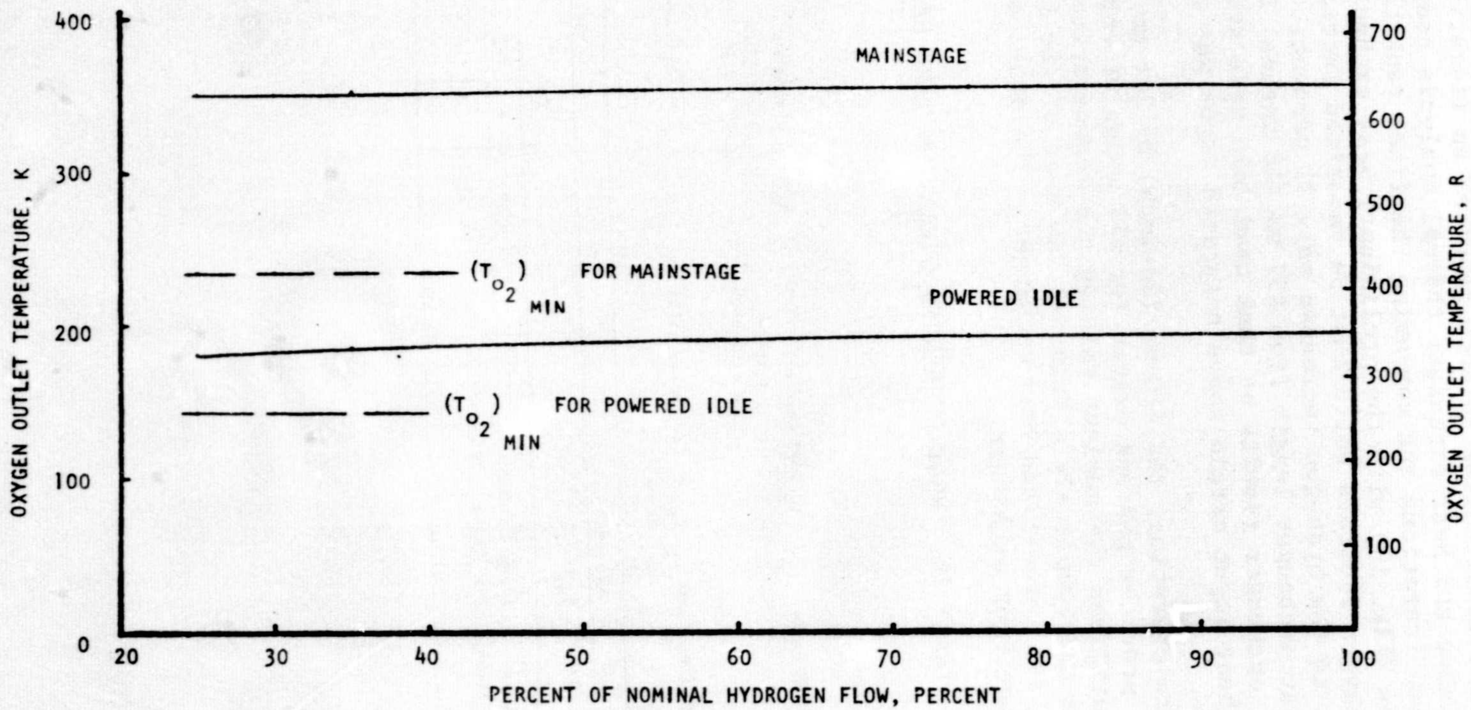


Figure 142. Heat Exchanger Hydrogen Flow Effects

Since the engine mathematical model does not perform detailed LOX head exchanger calculations, the final engine balance requires an iterative process involving the engine balance and heat exchanger thermal analysis computer programs. After completing these iterations and comparing the final tank head idle fuel and oxidizer flowrates (Fig. 10) with the preliminary heat exchanger flowrates shown in Fig. 11, the oxygen flowrate which must be vaporized increased by 46 percent and the heat input to the hydrogen increased only 21 percent. This resulted in an increase in heat exchanger length from 457 mm (18 inches) to 610 mm (24 inches). The final heat exchanger results at tank head idle mode are shown in Table 16. A 0.8 percent heat input margin above saturated vapor was obtained.

For steady-state operation, the 610-mm (24-inch) by 216-mm (8.5-inch) panel LOX heat exchanger provides gaseous oxygen for all modes of engine operation. This configuration utilizes the coolant exiting the regeneratively cooled nozzle as the heat source and completely eliminated the need of the hot preburner gas and, therefore, the three-fluid heat exchanger. The panel configuration offers a simple, compact heat exchanger.

TABLE 16. HEAT EXCHANGER OPERATION TANK HEAD IDLE

L = 457 mm (24 inch)

O_2: 70 Channels
1.27 x 1.52 mm
(0.05 x 0.06 inch)

H_2: 70 Channels
1.52 x 1.52 mm
(0.06 x 0.06 inch)

Thrust Chamber Conditions: P_c = 62 kPa (9 psia)
MR = 2.0

Hydrogen								Oxygen							
$\dot{w}_{H_2}$		T_{H_2}, IN		T_{H_2}, OUT		ΔP_{H_2}		$\dot{w}_{O_2}$		T_{O_2}, IN		T_{O_2}, OUT		ΔP_{O_2}	
kg/s	(lb/sec)	K	(R)	K	(R)	kPa	(psi)	kg/s	(lb/sec)	K	(R)	K	(R)	kPa	(psi)
0.0027	(0.006)	652	(1174)	346	(624)	18.6	~(2.7)	0.056	(0.1255)	91.6	(165)	97.2	(175.2)	2.34	~(0.34)

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SUMMARY OF PROGRAM RESULTS

The studies performed under this contract indicate that it is feasible to combine the components in the original baseline engine configuration described into a workable Powerhead Breadboard Assembly. Initial cycle balances on the original baseline configuration showed a heat imbalance on the heat exchanger, both at tank idle and powered idle mode. As a result, the three fluid heat exchanger shown in the original baseline configuration located in the oxidizer turbine inlet duct was relocated to the thrust chamber nozzle discharge line and converted to a two-fluid device in the final PBA. This simplified the heat exchanger and provided a better heat balance during idle modes. A pressure drop limiting valve was retained in a bypass circuit around the heat exchanger to maintain a reasonable pressure drop under mainstage flowrates.

Requirements were defined and specifications written for each valve application. Where possible existing valves were selected for each application. A layout of the existing major components specified in the original baseline configuration including the new heat exchanger and selected valves was completed. A stress analysis showed that all the proposed line routings and designs were structurally feasible.

Cycle balances conducted on the final powerhead breadboard assembly configuration shows feasible steady-state operation at tank head idle mode, powered idle mode, and mainstage at mixture ratios from 5.5 to 6.5. Transient cycle studies show the feasibility of start transitions from tank head idle to powered idle to mainstage. Present cycle transients do not indicate a need for a servo-controlled main fuel valve for either transient or steady-state engine operation.

An alternative configuration was developed which avoids mechanically locking the turbopump rotors during tank head idle mode by bypassing flow from the preburner directly to the main injector. This permits use of the cavitating venturi main fuel valve while still providing normal heat exchanger operation.

Cycle studies completed on this study show that the final power head breadboard configuration should be capable of performing tank head idle mode, powered idle mode, and mainstage from mixture ratios of 5.5 to 6.5.

APPENDIX A

ASE CONTROLS SPECIFICATION 1D

PROJECT: Advanced Space Engine (ASE)

SUBJECT: Preburner LOX valve and injector LOX valve

FUNCTION: These valves are required to throttle liquid oxygen (LOX) to the ASE preburner and main injector respectively, ultimately to control thrust and mixture ratio. These valves are used in a closed-loop servo system, actuated by an electric motor with position feedback.

EFFORT: A preburner LOX valve and an injector LOX valve are needed to perform the above functions and to satisfy the following conditions:

1. Fluid Service: Liquid oxygen in accordance with MIL-P-25508

2. Temperature:

Fluid	108 K (195 R) Nominal
Environment	TBD
Storage	TBD

3. Fluid Pressure: 35 232 kPa (5110 psig) maximum

4. Flowrate:

Preburner LOX valve	1.729 kg/s (3.8127 lb/sec) nominal at MR = 6.0
Injector LOX valve	14.71 kg/s (32.44 lb/sec) nominal at MR = 6.0

5. Delta P:

Preburner LOX valve	262 kPa (38 psid) maximum full open
Injector LOX valve	1930 kPa (280 psid) maximum full open

6. Full Open Flow Area:

Preburner LOX valve	69.69 mm^2 (0.10802 sq in.) (effective)
Injector LOX valve	208 mm^2 (0.32257 sq in.) (effective)

7. Leakage Rate:

Internal Leakage	1640 cc/min (100 scim) He maximum overpressure and temperature range
Shaft Seal Leakage	164 cc/min (10 scim) He maximum overpressure and temperature range

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8. **Materials:**

Shaft Seal	SP-211
Ball Seal	SP-211

9. Seal Concept:

Shaft	Delta Seal
Ball	Delta Seal

10. Instrumentation: Continuous position indication

11. Installation Concept:

Preburner LOX valve	Flange to 15.87 mm (0.625) ID line
Injector LOX valve	Flange to 31.75 mm (1.250) ID line

12. Actuator: Electric motor

13. Cycle Life: 100 duty cycles

14. Duty Cycle: The valve must open stop-to-stop, throttle for 1 minute out of 10 minutes and then close from stop-to-stop.

15. Response: Slew rate open-to-close or close-to-open. Not to exceed 500 milliseconds.

16. Valve Type: Ball

17. Special Features:

Preburner LOX valve	CLOSED fail safe position
Injector LOX valve	CLOSED fail safe position

ASE CONTROLS SPECIFICATION: 2B

PROJECT: Advanced Space Engine (ASE)

SUBJECT: LH_2 suction valve and LOX suction valve

FUNCTION: The function of the suction valves, which are located at the inlets to the low pressure pumps, is to provide positive shutoff of the propellants when the engine is not operating.

EFFORT: An LH_2 suction valve and a LOX suction valve are needed to perform the above functions and to satisfy the following conditions:

1. Fluid Service:

   Liquid hydrogen in accordance with MIL-P-27201

   Liquid oxygen in accordance with MIL-P-25508

2. Temperature:

	LH_2 Suction Valve	LOX Suction Valve
Fluid	20.3 to 22.2 K (36.5 to 40 R)	90 to 95.5 K (162 to 172 R)
Environment	TBD	TBD
Storage	TBD	TBD

3. Fluid Pressure:

Liquid Hydrogen	172 kPa (25 psig) maximum
Liquid Oxygen	172 kPa (25 psig) maximum

4. Flowrate:

Liquid Hydrogen	2.906 kg/s
Liquid Oxygen	16.89 kg/s (37.24 lb/sec)

5. Delta P: 6.89 kPa (1.0 psid) maximum

	LH_2 Suction Valve	LOX Suction Valve
6. Line Size:		
Inlet	TBD	TBD
Outlet	TBD	TBD

7. Leakage Rate:

Internal Leakage	1640 cc/min (100 scim) He maximum overpressure and temperature range
Shaft Seal Leakage	164 cc/min (10 scim) He maximum overpressure and temperature range

8. Materials:

Shaft Seal	SP-211 or TFE
Ball Seal	Blue Teflon Thermech Tecfluorfil BF 1 or SP-211
Actuator Seal	Mylar

9. Seal Concept:

Shaft	Delta Seal
Ball	Delta Seal
Actuator	Lip Seal

10. Instrumentation:

    Limit position indication

11. Installation Concept: TBD

12. Actuator: Pneumatic open, spring close, 2758 kPa (400 psig) helium

13. Cycle Life: 1000 cycles minimum

14. Response: Signal-to-open or signal-to-close. Not to exceed 1.0 second.

15. Valve Type: Ball

16. Special Features:

LH_2 Suction Valve	CLOSED fail safe position
LOX Suction Valve	CLOSED fail safe position

ASE CONTROLS SPECIFICATION: 3C

PROJECT: Advanced Space Engine (ASE)

SUBJECT: Fuel shunt valve

FUNCTION: The fuel shunt valve is installed to provide a fuel flow path in parallel with the heat exchanger. In the tank head idle mode of operation, the valve remains closed and all fuel flow is through the heat exchanger. In the pumped idle mode of operation, the valve is partially open with a differential pressure greater than the cracking pressure. In the mainstage mode of operation, the valve is fully open to provide a low-resistance flow path for heat exchanger bypass.

EFFORT: A 2-way normally closed fuel shunt valve is needed to perform the above functions and to satisfy the following conditions:

1. Fluid Service: Gaseous hydrogen in accordance with MIL-P-27201

2. Temperature:

Fluid	20.3 to 556 K (36.5 to 1000 R)
Environment	TBD
Storage	TBD

3. Fluid Pressure: 34 473 kPa (5000 psig) maximum (including surge)

4. Flowrate: 0.642 kg/s (1.4145 lb.sec) maximum

5. Delta P: 689 kPa (100 psid) maximum at maximum flowrate, pressure, and temperature.

6. Cracking Pressure: 345 $\pm$34.5 kPa (50 $\pm$5 psid)

7. Full Open Pressure: Cracking pressure plus 34.5 kPa (5 psid)

8. Leakage:

   Internal - 1640 cc/min (100 scim) He maximum at room temperature with increasing pressure in the 0 to 276 kPa (40 psig) range.

   External - Zero throughout pressure range.

9. Seal Concept:

Actuator	TBD
Seat	Metal-to-Metal

10. Instrumentation: None

11. Installation Concept: Weld stub out

12. Cycle Life: 1000 cycles

13. Valve Type: Poppet

14. Fail Safe Position: Closed

ASE CONTROLS SPECIFICATION: 4C

PROJECT: Advanced Space Engine (ASE)

SUBJECT: GO_2 Shutoff Valve

FUNCTION: The GO_2 shutoff valve is used during tank head idle to pass the oxidizer flow from upstream of the main chamber oxidizer valve through the heat exchanger, and then back into the main injector. The valve is installed between the heat exchanger and the main injector.

EFFORT: A 2-way normally closed GO_2 shutoff valve is needed to perform the above function and to satisfy the following conditions:

1. Fluid Service:

   Gaseous oxygen in accordance with MIL-P-25508

2. Temperature:

Fluid	108 K (195 R) nominal
Environmental	TBD
Storage	TBD

3. Fluid Pressure:

System	35 232 kPa (5110 psig) maximum
Operating	420 kPa (61 psig) maximum

4. Flowrate:

   0.055 5 kg/s (0.1225 lb/sec) with 138 kPa (~20 psia) inlet pressure and 68.9 kPa (~10 psia) injection pressure.

   0.060 7 kg/s (0.1338 lb/sec) with 379 kPa (~55 psia) inlet pressure and 72.4 kPa (~10.5 psia) injection pressure.

5. Delta P: Must meet requirements of item 4 under nominal temperature conditions.

6. Leakage Rate:

   Internal Leakage - 1640 cc/min (100 scim) He maximum overpressure and temperature range.

   External leakage - Zero with leak test solution over the pressure and temperature range.

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7. Instrumentation: None

8. Installation Concept: Weld stub outs

9. Cycle Life: 1000 cycles

10. Valve Type: Poppet

11. Fail-Safe Position: Closed

ASE CONTROLS SPECIFICATION: 5B

PROJECT: Advanced Space Engine (ASE)

SUBJECT: GO_2 ignition valve

FUNCTION: The GO_2 ignition valve controls the flow of oxidizer to the igniters of the main chamber and the preburner.

EFFORT: A 2-way normally closed direct solenoid operated GO_2 ignition valve is needed to perform the above functions and to satisfy the following conditions:

1. Fluid Service:

   Gaseous oxygen in accordance with MIL-P-25508

2. Temperature:

Fluid	108 to 294 K (195 to 530 R)
Environment	TBD
Storage	TBD

3. Fluid Pressure: System - 35 232 kPa (5110 psig) maximum

4. Flowrate: 0.023 kg/sec (0.052 lb/sec)

5. Delta P: 13 790 kPa (2000 psid) maximum at 108 K (195 R)

6. Equivalent Sharp Edge Orifice Diameter (C_d = 0.7): 0.45 mm (0.018 inch) diameter minimum

7. Leakage Rate:

   Internal Leakage - 1640 cc/min (100 scim) He maximum overpressure and temperature range
   External Leakage - zero

8. Materials: Compatible with fluid

9. Instrumentation: None

10. Installation Concept: Weld stub out

11. Cycle Life: 10 000 cycles minimum

12. Maximum ON Time: 20 minutes

13. Response: Signel-to-full open or signal-to-full close. Not to exceed 50 milliseconds.

14. Valve Type: Poppet

15. Special Features: CLOSED fail safe position

ASE CONTROLS SPECIFICATION: 6B

PROJECT: Advanced Space Engine (ASE)

SUBJECT: GH_2 ignition valve

FUNCTION: The GH_2 ignition valve controls the flow of fuel to the igniters of the main chamber and the preburner.

EFFORT: A 2-way normally closed direct solenoid operated GH_2 ignition valve is needed to perform the above functions and to satisfy the following conditions:

1. Fluid Service: Gaseous hydrogen in accordance with MIL-P-27201
2. Temperature:

Fluid	75 to 302 K (135 to 544 R)
Environment	TBD
Storage	TBD

3. Fluid Pressure: System - 27 579 kPa (4000 psig) maximum
4. Flowrate: 0.025 kg/s (0.056 lb/sec)
5. Delta P: 13 790 kPa (2000 psid) maximum at 177 K (319 R)
6. Equivalent Sharp Edge Orifice Diameter (C_d = 0.7): 1.27 mm (0.050 inch) diameter minimum
7. Leakage Rate:

   Internal Leakage - 1640 cc/min (100 scim) He maximum overpressure and temperature range

   External Leakage - zero
8. Materials: Compatible with fluid
9. Instrumentation: None
10. Installation Concept: Weld stub out
11. Cycle Life: 10 000 cycles minimum
12. Maximum ON Time: 20 minutes
13. Response: Signal-to-full open or signal-to-full close. Not to exceed 50 milliseconds.
14. Valve Type: Poppet
15. Special Features: CLOSED fail safe position

ASE CONTROLS SPECIFICATION: 7A

PROJECT: Advanced Space Engine (ASE)

SUBJECT: Fuel bypass valve

FUNCTION: The fuel bypass valve is located downstream of the high pressure fuel pump and is opened during tank head idle mode to allow fuel to bypass the thrust chamber coolant jacket, preburner, and turbines and thus prevent turbopump rotation. The transition to pumped idle mode is accomplished by closing the fuel bypass valve thereby increasing the fuel flow to the turbines, which initiates turbopump rotation.

EFFORT: A 2-way normally closed direct solenoid operated fuel bypass valve is required to perform the above functions and to satisfy the following conditions:

1. Fluid Service: Liquid hydrogen in accordance with MIL-P-27201
2. Temperature:

Fluid	20.3 to 55.5 K (36.5 to 100 R)
Environment	TBD
Storage	TBD

3. Fluid Pressure: System - 33 095 kPa (4800 psig) maximum
4. Flow Rate: TBD
5. Delta P: 165 kPa (24 psid) maximum
6. Equivalent Sharp Edge Orifice Diameter (C_d = 0.65): 3.81 mm (0.150 inch) diameter minimum
7. Leakage Rate: External Leakage - zero from 0 to 4500 psig
8. Materials: Compatible with fluid
9. Seat Seal Concept: Metal-to-metal
10. Instrumentation: None
11. Installation Concept: Weld stub out
12. Cycle Life: 10,000 cycles minimum
13. Maximum ON Time: 3 minutes
14. Response: Signal-to-full open or signal-to-full close. Not to exceed 100 milliseconds.
15. Valve Type: Poppet
16. Special Features:
    a) Bypass orifice 0.45 mm^2 (0.0007 sq in.) (effective area)
    b) CLOSED fail safe position

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ASE CONTROLS SPECIFICATION: 8B

PROJECT: Advanced Space Engine (ASE)

SUBJECT: Main fuel valve

FUNCTION: The fuel valve is located downstream of the second stage of high pressure fuel pump and controls the hydrogen flow into the thrust chamber cooling jacket. A cavitating venturi function is required based upon pumped idle mode requirements. During pumped idle operation, the venturi throat area is set to cavitate to provide hydraulic isolation of the fuel pump from boiling instability, which occurs in the thrust chamber cooling jacket when the hydrogen coolant pressure is subcritical. At full thrust the valve is scheduled to control fuel flow to the engine and, with other valves, provides the desired mixture ratio.

EFFORT: A main fuel valve is needed to perform the above functions and to satisfy the following conditions:

1. Fluid Service: Liquid hydrogen in accordance with MIL-P-27201

2. Temperature:

Fluid	20.3 to 55.5 K (36.5 to 100 R)
Environment	TBD
Storage	TBD

3. Fluid Pressure: 34 474 kPa (5000 psig) maximum (including surge)
4. Flowrate: 2.741 kg/s (6.042 lb/sec) nominal at MR = 6.0
5. Delta P: 138 kPa (20 psid) maximum full open
6. Full Open Flow Area: 403 mm^2 (0.6247 sq in.) (effective)
7. Leakage Rate: Shaft Seal Leakage - 164 cc/min (10 scim) He maximum overpressure and temperature range
8. Materials: Shaft Seal SP-211
9. Seal Concept: Shaft Delta Seal
10. Instrumentation: Continuous position indication
11. Installation Concept: Flanged
12. Actuator: Electric motor
13. Cycle Life: 100 duty cycles
14. Duty Cycle: The valve must open stop-to-stop throttle for one minute out of 10 minutes and then close from stop-to-stop.
15. Response: Slew rate open-to-close or close-to-open. Not to exceed 1.0 second.

16. Valve: Ball

17. Special Features:

    a. The cavitating venturi function, having an effective area of 49.5 mm^2 (0.0768 sq in.) to be effective when valve is in closed position.

    b. Provide kit design for breadboard engine replacing cavitating venturi function above with SP-211 ball seal for positive shut off with leakage rate of 3280 cc/min (200 scim) overpressure and temperature range.

ASE CONTROLS SPECIFICATION: 9A

PROJECT: Advanced Space Engine (ASE)

SUBJECT: GO_2 throttle valve

FUNCTION: The GO_2 throttle valve controls GO_2 flow to the main injector during the tank head idle mode.

EFFORT: A GO_2 throttle valve is required to perform the above functions and to satisfy the following conditions:

1. Fluid Service: Gaseous oxygen in accordance with MIL-P-25508
2. Temperature:

Fluid	165 to 235 K (298 to 423 R)
Environment	TBD
Storage	TBD

3. Fluid Pressure: System - 35 418 kPa (5137 psig) maximum
4. Flowrate: TBD
5. Delta P: 345 kPa (50 psid) maximum
6. Flow Area: TBD
7. Leakage Rate:

   Shaft Seal Leakage - 164 cc/min (10 scim) He maximum over-pressure and temperature range.

   Internal Leakage - Maximum closed leakage less than 10% of full open flow.

8. Materials: Shaft Seal SP-211
9. Seal Concept: Shaft Delta Seal
10. Instrumentation: Continuous position indication
11. Installation Concept: Flanged
12. Actuator: Electric motor
13. Cycle Life: 100 Duty Cycles
14. Duty Cycle: The valve must open stop-to-stop, throttle for 1 minute out of 10 minutes and then close from stop-to-stop.
15. Response: Signal-to-open or signal-to-close. Not to exceed 1.0 second
16. Valve Type: Ball
17. Special Features: None

ASE CONTROLS SPECIFICATION: 10A

PROJECT: Advanced Space Engine (ASE)

SUBJECT: GO_2 check valve

FUNCTION: The GO_2 check valve is located in the LOX tank pressurization line downstream of the GO_2 heat exchanger and it prevents GO_2 flow to the LOX tank during tank head idle mode.

EFFORT: A GO_2 check valve is needed to perform the above functions and to satisfy the following conditions.

1. Fluid Service: Gaseous oxygen in accordance with MIL-P-25508
2. Temperature:

Fluid	108 to 294 K (195 to 530 R)
Environment	TBD
Storage	TBD

3. Fluid Pressure: System - 35 232 kPa (5110 psig) maximum
4. Flowrate:

Tank Head Idle	0
Pumped Idle	0.0408 kg/sec (0.090 lb/sec) at 143 K (258 R)
Full Thrust	0.0608 kg/sec (0.134 lb/sec) at 235 K (423 R)

5. Delta P: 345 kPa (50 psid) maximum
6. Cracking Pressure: 41.4 to 68.9 kPa (6 to 10 psig)
7. Leakage Rate: Internal Leakage - 164 cc/min (10 scim) He maximum to 172 kPa (25 psig) and temperature range of 88.9 to 294 K (160 to 530 R)
8. Materials: Compatible with fluid
9. Seal Concept: Seal - Teflon O-ring
10. Instrumentation: None
11. Installation Concept: Weld stub out
12. Cycle Life: 10,000 cycles minimum
13. Valve Type: Poppet

ASE CONTROLS SPECIFICATION: 11

PROJECT: Advanced Space Engine (ASE)

SUBJECT: Electric actuators for operation of preburner LOX valve, injector LOX valve, and main fuel valve.

FUNCTION: The electric actuators are required to actuate and maintain position of the valves in a closed-loop servo system.

EFFORT: Electric actuators are required to perform the above functions and to satisfy the following conditions.

1. Type: Electro mechanical/rotary
2. Actuation Time: Slow rate open-to-close or close-to-open not to exceed 1 second maximum; 500 milliseconds goal
3. Travel: 90 degrees nominal
4. Rated Torque:

   Preburner valve - 11.3 N.m (100 in.-lb) at 28 VDC

   Injector Valve - 22.6 N.m (200 in.-lb) at 28 VDC

   Fuel Valve - 11.3 N.m (100 in.-lb) at 28 VDC)

5. Restraint Torque:

   Preburner Valve - 5.6 N.m (50 in.-lb) minimum

   Injector Valve - 11.3 N.m (100 in.-lb) minimum

   Fuel Valve - 11.3 N.m (100 in.lb) minimum

6. Voltage: 28 $\pm$4 Vdc
7. Current:

   Preburner Valve - TBD AMPS maximum

   Injector Valve - TBD AMPS maximum

   Fuel Valve - TBD AMPS maximum

8. Operating Temperature: 200 to 347 K (-100 to 165 F)
9. Environmental Pressure: Sea level to hard vacuum
10. Duty Cycle: The actuator must open the valve stop-to-stop, throttle the valve for 1 minute out of 10 minutes and then close the valve stop-to-stop.
11. Operating Life: 100 duty cycles

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12. Interface:

    Mounting - TBD

    Drive - TBD

13. Electrical Connector: TBD

14. Special Features:

    a. Continuous position indication for servo control operation.

    b. Mechanical override feature to allow 300 millisecond valve closing using an externally applied closing shaft torque.

APPENDIX B

ASE POWERHEAD BREADBOARD ASSEMBLY INSTRUMENTATION LIST

SYSTEM: LH_2 TURBOPUMP

PARAMETER	RANGE METRIC	RANGE ENGLISH	DIGITAL	DIGR	OSC	FM TAPE	COMMENTS
Inlet Pressure No. 1	689 kPa	(100 psig)	X				Piezometer Ring
Inlet Pressure No. 2	1379 kPa	(200 psig)	X	X	X		Close Coupled
Inlet Temperature No. 1	22 to 33 K	(-420 to -400 F)	X	X	X		RTB
Inlet Temperature No. 2	22 to 255 K	(-420 to 0 F)	X				RTB
Discharge Temperature No. 1	22 to 33 K	(-420 to -400 F)					
Discharge Temperature No. 2	22 to 255 K	(-420 to 0 F)	X				RTB
Discharge Pressure	34 474 kPa	(5000 psig)	X	X	X		Piezometer Ring
1st Stage Impeller Discharge Pressure	13 790 kPa	(2000 psig)	X		X		
1st Stage Crossover Injector Pressure	13 790 kPa	(2000 psig)	X				
1st Stage Crossover Mid Pressure	13 790 kPa	(2000 psig)	X				
1st Stage Crossover Discharge Pressure	13 790 kPa	(2000 psig)	X		X		
2nd Stage Impeller Front Shroud Pressure	20 684 kPa	(3000 psig)	X				
2nd Stage Differential Discharge Pressure	34 474 kPa	(5000 psig)	X		X		
3rd Stage Impeller Discharge Pressure	34 474 lPa	(5000 psig)	X	X	X		
Balance Piston Cavity Pressure	34 474 kPa	(5000 psig)	X	X	X		
Balance Piston Sump Pressure	34 474 kPa	(5000 psig)	X	X	X		
Bearing Coolant Pressure	1379 kPa	(200 psig)	X		X		
Bearing Coolant Temperature	22 to 255 K	(-420 to 0 F)	X	X	X		
Turbine Bearing Coolant Temperature	22 to 255 K	(-420 to 0 F)	X	X	X		
Pump Speed	2000 Hz	(120,000 RPM)	X	X	X	X	High Speed Oscill.
Axial Proximity Inducer	Tape FM				X	X	
Tangential Proximity	Tape FM				X	X	
Radial Proximity Inducer	Tape FM				X	X	
Axial Acceleration	20 grms				X	X	
Tangential Acceleration	20 grms				X	X	
Radial Acceleration	20 grms				X	X	High Speed Oscill.
Surface Temperature No. 1	255 to 1367 K	(0 to 2000 F)	X				
Surface Temperature No. 2	255 to 1367 K	(0 to 2000 F)	X				
Surface Temperature No. 3	255 to 1367 K	(0 to 2000 F)	X				
Surface Temperature No. 4	255 to 1367 K	(0 to 2000 F)	X				
1st Stage Nozzle Pressure	34 474 kPa	(5000 psig)	X	X	X		
Turbine Manifold Pressure	34 474 kPa	(5000 psig)	X				
Turbine Seal Pressure	34 474 kPa	(5000 psig)	X		X		
Turbine Static Discharge Pressure	20 684 kPa	(3000 psig)	X	X	X		
Turbine Discharge Temperature	255 to 1367 K	(0 to 2000 F)					

SYSTEM: LOX TURBOPUMP

PARAMETER	RANGE METRIC	RANGE ENGLISH	DIGITAL	DIGR	OSC	FM TAPE	COMMENTS
Tank Pressure	3447 kPa	(500 psig)	X	X			
Inlet Pressure	1379 kPa	(200 psig)	X	X	X		Piezometer Ring
Inlet Temperature	177 to 89 K	(-250 to -300 F)	X	X			RTB
Impeller Discharge Pressure	34 474 kPa	(5000 psig)	X	X			
Diffuser Discharge Pressure	34 474 kPa	(5000 psig)	X				
Pump Discharge Pressure	34 474 kPa	(5000 psig)	X	X	X		Piezometer Ring X-Y Plotter
Pump Discharge Temperature	200 to 89 K	(-100 to -300 F)	X				RTB
Balance Piston Cavity Pressure	34 474 kPa	(5000 psig)	X	X			
Balance Piston Sump Pressure	34 474 kPa	(5000 psig)	X	X			
Balance Piston Return Flow Pressure	34 474 kPa	(5000 psig)	X				
Balance Piston Return Flow Temperature	117 to 89 K	(-250 to -300 F)	X	X			Pump Brg. RTB Supplied
Inlet Static Pressure	34 474 kPa	(5000 psig)	X	X	X		
Inlet Temperature No. 1	255 to 1367 K	(0 to 2000 F)	X				Wall + 0.150"
Inlet Temperature No. 2	255 to 1367 K	(0 to 2000 F)	X	X			Core Temperature
Nozzle Downstream Pressure	34 474 kPa	(5000 psig)	X				
Exhaust Static Pressure	34 474 kPa	(5000 psig)	X				
Exhaust Temperature	200 to 1367 K	(-100 to +2000 F)	X				
Primary LOX Seal Drain Line Pressure	689 kPa	(100 psig)	X	X			
Primary LOX Seal Drain Line Temperature	89 to 311 K	(-300 to +100 F)	X	X			Thermocouple
Primary Hot Gas SealOrifice Upstream Pressure	689 kPa	(100 psig)	X				
Primary Hot Gas Seal Drain Orifice Upstream Temperature	255 to 1367 K	(0 to 2000 F)	X				Thermocouple
Sec Hot Gas Seal Drain Line Pressure	3447 kPa	(500 psig)	X				
Sec Hot Gas Seal Drain Line Temperature	255 to 1367 K	(0 to 2000 F)	X				Thermocouple

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ASE POWERHEAD BREADBOARD ASSEMBLY INSTRUMENTATION LIST (Continued)

SYSTEM: LOX TURBOPUMP

PARAMETER	RANGE METRIC	RANGE ENGLISH	DIGITAL	DIGR	OSC	FM TAPE	COMMENTS
Sec Hot Gas Seal Drain Orifice Upstream Pressure	689 kPa	(100 psig)	X				
Sec Hot Gas Seal Drain Orifice Temperature	255 to 1367 K	(0 to 2000 F)	X				Thermocouple
Intermediate Seal Purge Pressure	3447 kPa	(500 psig)	X	X			
Intermediate Seal Purge Temperature	200 to 311 K	(-100 to +100 F)	X				Thermocouple
Rear Bearing Coolant Supply Pressure	34 474 kPa	(5000 psig)	X				
Rear Bearing Coolant Supply Temperature	5 to 116 K	(-450 to -250 F)	X				Thermocouple
Rear Bearing Coolant Drain Pressure	6895 kPa	(1000 psig)	X	X			
Rear Bearing Coolant Drain Temperature	5 to 116 K	(-450 to -250 F)	X	X			Thermocouple
Rear Bearing Coolant Orifice Pressure	2413 kPa	(350 psig)	X	X			
Rear Bearing Coolant Orifice Temperature	200 to 311 K	(-100 to +100 F)	X	X			Thermocouple
Axial Proximity Inducer	Tape FM				X	X	
Radial Proximity Inducer No. 1	Tape FM				X	X	
Radial Proximity Inducer No. 2	Tape FM				X	X	90 Degree from No. 1
Pump Axial Acceleration	Tape FM				X	X	
Pump Radial Acceleration	Tape FM				X	X	
Turbine Radial Acceleration	Tape FM				X	X	
Pump Speed	1667 Hz	(1000,000 RPM)	X	X	X	X	

SYSTEM: PREBURNER

PARAMETER	RANGE METRIC	RANGE ENGLISH	DIGITAL	DIGR	OSC	FM TAPE	COMMENTS
Igniter LOX Venturi Upstream Pressure	34 474 kPa	(5000 psig)	X				
Igniter LOX Venturi Upstream Temperature	200 to 367 K	(-100 to +200 F)	X				1-C
Igniter LOX Injection Pressure	34 474 kPa	(5000 psig)	X	X	X		
Igniter LOX Injection Temperature	200 to 367 K	(-100 to +200 F)	X				1-C
Igniter Fuel Venturi Upstream Pressure	34 474 kPa	(5000 psig)	X				
Igniter Fuel Venturi Upstream Temperature	200 to 367 K	(-100 to +200 F)	X				1-C
Igniter Fuel Injection Pressure	34 474 kPa	(5000 psig)	X	X	X		
Igniter Fuel Injection Temperature	200 to 367 K	(-100 to +200 F)	X				1-C
LOX Venturi Upstream Pressure	34 474 kPa	(5000 psig)	X	X			
LOX Venturi Upstream Temperature	89 to 255 K	(-300 to 0 F)	X	X			RTB
LOX Venturi ΔP	689 kPa	(100 psid)	X	X			
LOX Injection Pressure	34 474 kPa	(5000 psig)	X	X	X		
LOX Injection Temperature	89 to 256 K	(-300 to 0 F)	X				RTB
MLV Position	TRACE		X		X		
Exciter Spark Command	0 to Vdc				X		
Exciter Spark Monitor	0 to 10 Vdc				X		
Fuel Venturi Upstream Pressure	34 474 kPa	(5000 psig)	X	X			
Fuel Venturi Upstream Temperature	22 to 256 K	(-420 to 0 F)	X	X			RTB
Fuel Venturi ΔP	1379 kPa	(200 psid)	X	X			
Fuel Injection Pressure	34 474 kPa	(5000 psig)	X	X	X		
Fuel Injection Temperature	22 to 256 K	(-420 to 0 F)	X	X			RTB
Chamber Pressure	34 474 kPa	(5000 psig)	X	X	X		
Combustion Temperature No. 1	256 to 1367 K	(0 to 2000 F)	X				C/A (.075")*
Combustion Temperature No. 2	256 to 1367 K	(0 to 2000 F)	X	X	X		C/A (.196")*
Combustion Temperature No. 3	256 to 1367 K	(0 to 2000 F)	X				C/A (.398")*
Combustion Temperature No. 4	256 to 1367 K	(0 to 2000 F)	X				C/A (.75")*
Turbine Inlet Static Pressure	34 474 kPa	(5000 psig)	X				
Ignition Detect Temperature No. 1	256 to 1367 K	(0 to 2000 F)	X				Thermocouple
Ignition Detect Temperature No. 2	256 to 1367 K	(0 to 2000 F)	X				Thermocouple
Ignition Detect Temperature No. 3	256 to 1367 K	(0 to 2000 F)	X				Thermocouple

SYSTEM: THRUST CHAMBER

PARAMETER	RANGE METRIC	RANGE ENGLISH	DIGITAL	DIGR	OSC	FM TAPE	COMMENTS
Igniter Oxidizer Orifice Temperature	200 to 366 K	(-100 to +200 F)	X				
Igniter Fuel Orifice Temperature	200 to 366 K	(-100 to +200 F)	X				
Fuel Injection Temperature	200 to 366 K	(-100 to +200 F)	X				
Oxidizer Injection Temperature	311 to 89 K	(+100 to -300 F)	X				
Igniter Oxidizer Orifice Pressure	20 684 kPa	(3000 psig)	X		X		
Igniter Fuel Orifice Pressure	20 684 kPa	(3000 psig)	X		X		
Igniter Fuel Injection Pressure	14 478 kPa	(2100 psig)	X	X	X		
Chamber Pressure	13 790 kPa	(2000 psig)	X	X	X		
Thrust, "A" Bridge Force	66 723 Newtons	(15,000 pound)	X	X	X		
Chamber Pressure	13 790 kPa	(2000 psig)	X	X			

ASE POWERHEAD BREADBOARD ASSEMBLY INSTRUMENTATION LIST (Concluded)

SYSTEM: THRUST CHAMBER

PARAMETER	RANGE METRIC	RANGE ENGLISH	DIGITAL	DIGR	OSC	FM TAPE	COMMENTS
Injector Fuel Pressure	14 478 kPa	(2100 psig)	X	X	X		
Igniter Oxidizer Manifold Pressure	14 478 kPa	(2100 psig)	X	X	X		
Oxidizer Injection Pressure	20 684 kPa	(3000 psig)	X	X	X		
Thrust, "B" Bridge Force	66 723 Newtons	(15,000 pound)	X				
175:1 Nozzle Coolant Pressure	689 kPa	(100 psid)	X				
175:1 Nozzle Coolant Outlet Pressure	27 579 kPa	(4000 psig)	X				
175:1 Nozzle Coolant Outlet Temperature	200 to 366 K	(-100 to +200 F)	X	X	X		
Oxidizer Flowrate	220 cps		X	X	X		
Liquid Hydrogen Flowrate	320 cps		X	X	X		
Ignition Detect Temperature	255 to 978 K	(0 to 1300 F)	X	X	X		
Ignition Detect Temperature	255 to 978 K	(0 to 1300 F)	X				
Ignition Detect Temperature	255 to 978 K	(0 to 1300 F)	X				

SYSTEM: HEAT EXCHANGER

PARAMETER	RANGE METRIC	RANGE ENGLISH	DIGITAL	DIGR	OSC	FM TAPE	COMMENTS
Heat Exchanger Downstream Fuel Pressure	34 474 kPa	(5000 psig)	X				
Heat Exchanger GOX Inlet Temperature	89 to 367 K	(-300 to +200 F)	X				
Heat Exchanger GOX Outlet Temperature	255 to 811 K	(0 to 1000 F)	X				
Heat Exchanger GOX Outlet Pressure	34 474 kPa	(5000 psig)	X		X		
Heat Exchanger GOX Inlet Pressure	34 474 kPa	(5000 psig)	X				
Heat Exchanger Outlet Delta Pressure	34 474 kPa	(500 psid)	X				

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2. Csomor, A. and R. Sutton, Small, High-Pressure Liquid Oxygen Turbopump, Interim Report, NASA CR-135211, Rockwell International/Rocketdyne Division, Canoga Park, California, Report No. R76-178, July 1977.